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Backache and Back Discomfort

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Conference Proceedings No.378

BACKACHE AND BACK DISCOMFORT

Papers presented at the Aerospace Medical Panel Specialists' Meeting held in
Pozzuoli, Italy from 8 to 10 October 1985.

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PREFACE

Backache and back discomfort in aircrew are serious economic and operational problems for many armed services. Temporary back discomfort may distract aircrew personnel and compromise the success of a mission, while chronic back pain may effectively remove them from active duty and require expensive treatment. Pilots of both helicopters and fixed-wing aircraft have often reported that both temporary and chronic pain appear during active flight duty. In the past, investigators have suggested that both the seated posture of aircrew and the vibration or shock transmitted by the seat during flight may be responsible for the pain.

The objective of this Specialists' Meeting was to bring those who had investigated the possible mechanical causes of backache in both the civilian and military ground-vehicle and aircraft environments together to consider the common underlying factors in these problems. Many topics were considered. These included:

- The epidemiology of back pain in drivers and pilots, considering both the posture and the vibrational environment as contributory factors;
- the biomechanics of the spine;
- the methods of evaluating individuals in order to predict their susceptibility to chronic back pain;
- the methods for treating and preventing back pain through education; and
- the potential for reducing the incidence of back pain in the design of current and future aircraft cockpits.

The data and conclusions presented at this Specialists' Meeting are often of a tentative nature, and emphasize the need for further research. They also stress the potential to dramatically reduce the incidence of both temporary discomfort and chronic pain in aircrew through the design of advanced aircraft cockpit systems. The seriousness of the problem, and the simplicity and effectiveness of some proposed solutions, should recommend these Proceedings to those involved in the design of military ground vehicles and aircraft, and those responsible for the health and effective use of aircrew in actual operations.

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1. INTRODUCTION

The Aerospace Medical Panel held a Specialist's Meeting on "Backache and Back Discomfort" at Accademia Aeronautica in Pozzuoli (Naples), Italy from October 8 to 10, 1985. Twenty-nine papers were given from eight NATO and two non-NATO countries.

2. THEME

The theme of the symposium was the recurring operational problem of backache and back discomfort in military personnel. Modern research techniques have identified many potential causes of back pain and back discomfort, and new approaches have been taken to reduce their effects on both military personnel and civilians. Of particular importance is the high frequency of low-back pain in both fixed-wing and helicopter aircraft, and in certain land vehicles such as armoured personnel carriers, main battle tanks, buses, and earth-moving machinery. Operators in some of these vehicles may be forced to assume constrained postures but all are exposed to vibration during the performance of their duties. The papers which were selected for this symposium gave an insight into "idiopathic" and drivers' low-back pain; its epidemiology in the general and military populations; the biomechanics of, and mechanical stresses on, the spine; and the ways in which this knowledge could be applied to improving the cockpit environment. The knowledge gained from the study of backache and back discomfort may be used by the aerospace community to improve the cockpits of current aircraft, and in the design and development of advanced cockpit environments.

3. PURPOSE AND SCOPE

The purpose of the symposium was to bring military and civilian specialists working in different disciplines together to consider the problems of back pain and back discomfort in vehicular environments; in particular, as they relate to the discomfort of aircrew in current and emerging aircraft. The scope was broad, in that it covered several aspects of the back-pain problem. Idiopathic low-back pain in the general population was considered from the point of view of posture and vehicular vibration as contributory factors, the conditions of the spine which predispose individuals to backache, the spine and task ergonomics, the methodology for predicting spinal instability, and "back-school" programmes for the prevention or treatment of recurrent back pain. The topics discussed under backache and back discomfort in the cockpit environment included methods of measurement, the effects of whole-body vibration and sitting posture on the spine, and the use of passive lumbar supports, improved seat cushions, and active anti-vibration seat cushions as preventative measures. The participants included military and civilian experts in epidemiology, orthopaedic medicine, pathophysiology, biomechanics, mechanical vibration, process modelling, anthropometry, task ergonomics, and design and operations engineering. Presentations were drawn from industry, defence and other governmental research laboratories, universities, military and civilian medical centers and health services, and private research institutions.

4. SYMPOSIUM PROGRAM

The papers for the symposium fell into five sessions that provided a continuum of topics which closely reflect current military and civilian research and practices in the study and prevention of backache and back discomfort.

The first session, Back Pain in Vehicles: Epidemiology, set the background for the symposium. The emphasis was on epidemiology as a means of identifying those factors which contribute to back disorders. Surveys were conducted by interview, questionnaire, the study of previous medical records, and objective medical examinations. Surveys of drivers' back pain were conducted for fixed- and rotary-wing aircraft, as well as in a variety of land vehicles (including wheel- and track-types for off-road, paved, or gravel conditions). The first eight papers made up this session.

The second session, Biomechanics and Biometrics of the Spine, consisted of five papers. This session dealt with information that is required in order to produce mathematical or engineering models of spinal geometry and mechanical behaviour; models which may be used to evaluate the effects of vibration and posture without exposing human populations to discomfort or the risk of injury.

The four papers that made up the third session, Response of Spine to Vibration, described how the spine behaves under loading to whole-body vibration for sitting or standing positions. Mathematical models, which incorporate the experimental observations, related dynamic vertebral column loading to fatigue-induced changes in spinal structures.

The four papers in the fourth session, Back Pain: Diagnosis, Prediction, and Prevention, discussed a novel method for diagnosing the severity of spinal segment defects, and some experiences in evaluating and predicting back pain in servicemen. The session ended with an important paper which discussed the cost effectiveness of implementing a structured back care education programme for the purpose of preventing recurrent back pain in military personnel.

The fifth session, Back Discomfort: Cockpit Environment and Remedial Measures, was comprised of eight papers that were mainly concerned with backache and back discomfort in the helicopter cockpit environment. Factors discussed, included muscle fatigue, spinal segment microtrauma, and diurnal changes in body height. A variety of short-term proposals for relieving back discomfort were addressed.

5. TECHNICAL EVAULATION

5.1 Back Pain in Vehicles: Epidemiology

The author of the first paper (Troup), after surveying the relevant literature, concluded that the cause of drivers' backache remains unknown. Although there is reliable evidence that driving is a contributory etiologic factor in clinically-treated patients with back pain, the role of severe vibrations and impact shocks from bad road conditions in the genesis of back pain is still unclear. What is required now is a series of experimentally-designed prospective studies to test the leading hypothetical causes of drivers' backache, rather than continuing with further surveys from retrospective clinical studies. Notwithstanding this requirement, substantial cost-benefit gains can be achieved by reducing occupationally-induced musculoskeletal pain through proper ergonomic vehicular redesigns.

A knowledge of the effects of whole-body vibration on back discomfort is sorely lacking. The authors of the second and third papers redressed this somewhat, by providing insight into the vibration environment of earth-moving machinery and its effects on operator discomfort. The first of these papers (Zerlett) discussed the various findings of an extensive epidemiological study of back disorders in operators of wheel- and track-type machinery with vibration in the frequency range from 1.5 to 10 Hz. Back discomfort was much more frequent in groups exposed to vibration for many years (70%) than in a comparable non-exposed control group (54%). Questionnaire results showed that lumbar discomfort was the most commonly-reported symptom (68.7%). Pathological changes in the lumbar spine, as indicated by X-rays, were statistically significantly more prevalent and occurred earlier in drivers with 10-years exposure to whole-body vibration than in the comparable control group. The other paper (Boulanger) addressed the inadequate vibration isolation of the seat suspension system in many types of earth-moving vehicles, and made recommendations, based on existing standards,for assessing the performance of these seats.

The fourth paper (Beevis) compared back pain in three groups of armoured fighting vehicle drivers: (a) M113 Armoured Personnel Carrier (APC) Motor Pool drivers, (b) M113 APC drivers attached to an infantry regiment ("RCR drivers"), and (c) main battle tank (Centurion) drivers. The number of driving hours per week was similar for the Motor Pool and Centurion drivers, but much less for the RCR drivers. The Pool and tank driving was mainly off-road. Questionnaire results indicated that 89% of Pool drivers, 46% of RCR drivers, and 55% of Centurion drivers suffered from back problems; values which are considered to be much higher than those found in a "normal" population of land vehicle drivers. A study of vehicle ride characteristics showed that Z-axis acceleration levels at the driver's seat were much higher for the off-road condition in the APC and exceeded ISO 2631 exposure limits. In the much heavier and slower Centurion tank, these accelerations were smaller than in the APC, and were not sensitive to different road conditions. The authors argued convincingly that back injury in Pool drivers (to the extent of lumbar disc herniation) occurred as a result of poor posture and a very intense vibration environment; and back pain in RCR and Centurion drivers, primarily from bad posture.

The fifth paper (Froom) described the responses to a questionnaire and medical survey taken from three groups of Israeli pilots: fighter, transport aircraft, and helicopter pilots. A significant finding was that, although helicopter pilots reported more low-back pain during and immediately after flight (34.5%, compared to 12.9% and 4.8% for fighter and transport pilots, respectively), they were no more prone to chronic back pain than the other two groups. Of those who reported chronic low-back pain, the fighter pilots suffered the most severely (25.6%, compared to 6.9% and 5.9% for transport and helicopter pilots, respectively). As a group, fighter pilots tended to have narrower posterior intervertebral disc spaces than did a control group of transport pilots. These findings support the idea that there are different forms of low-back pain in the military population, which can be distinguished by their time-course and severity; and that the biomechanical causes of low-back pain are different in different aircraft.

The paper by Burmeister and Thoma reported on the results of a survey (by questionnaire) on backache and flying duty in pilots of jet and propeller-driven aircraft. About one-half of the respondents suffered (mainly) lumbar back pain. Although the frequency of back pain appears to increase with total flying hours, this relationship disappears when the age of the respondents is taken into account. Of the pilots who experienced back pain, the jet pilots were more likely to describe their pain as intermittent or "stabbing", while prop pilots described it as "dragging". Whether or not they experienced back pain, pilots in both groups felt that both the sitting posture and the coldness of the seats were uncomfortable. Jet pilots blamed G-loading as a source of back pain, but neither group considered vibration as an important causal factor. The authors recommended that seat designs avoid excessive rearward pelvic tilt, which contributes to intervertebral disc stress and muscle fatigue. One-half of the pilots felt that flying impaired their health; this was particularly true for those suffering backache. This belief, and its effect on morale, can only be counteracted by the dissemination of reliable information on the subject to pilots.

The sixth paper (Shanahan) discussed the etiologic factors of back discomfort in U.S. Army helicopter aircrew. Questionnaire results showed that 72.8% of pilots experienced back discomfort, most frequently in the lower back (70% of cases) and buttocks (16.6%). In 50.1% of respondents, the low-back pain was of a transient nature, lasting for 24 hours or less, and was ascribed to the slumped and asymmetrical posture that helicopter pilots must assume to effectively operate the controls. In a second group of more experienced helicopter pilots (14.5% of respondents), persistent pain was reported that lasted longer than 48 hours and resembled the low-back pain in clinical cases. (The author of the twenty-fourth paper (Bowden) compared this chronic pain with that of "idiopathic low-back pain" in its chronic aspects in the civilian population.) Compelling arguments were given that the persistent pain group may have developed spinal pathologies that worsen through repeated mission exposure to a poor postural environment. The vibration to which helicopter aircrew are exposed may or may not aggravate the backache. The author noted that, even though vibration-reducing designs have been implemented in current helicopters, back pain continues to be a problem. A disturbing finding in this paper concerned two methods aircrew have used to alleviate the symptoms of back discomfort: a significant number (28.4%) of aircrew have rushed helicopter missions; while 7.5% have actually refused theirs. Since about one-third of aircrew first noted symptoms of back discomfort within the first two hours, it might be prudent, for the sake of mission safety and effectiveness, for field commanders to restrict helicopter sorties to that duration.

The seventh paper (Westgaard) presented evidence for a causal relationship between continuous, low-intensity muscle loads of long duration and the risk of developing musculoskeletal illness. The suggestion was made that, during active duty, the constrained posture and other factors to which aircraft pilots are exposed could keep muscles in a constant state of tension, thereby contributing to back discomfort. A novel hypothesis put forth by these authors was that vibration may activate muscle-spindle sensory organs, causing facilitory action in spinal motoneurons, which could lead to increased muscle contractions.

5.2 Biomechanics and Biometrics of the Spine

The eighth paper (Quandieu) provided a valuable review of what is known about the mechanical properties of the constituent elements of the spine. The author described some studies in detail, notably those of the group at Centre d'Etudes et de Recherches de Medecine Aerospaciales, Paris, France, using animals with accelerometers implanted in individual vertebrae, and a study of the problems in obtaining accurate motion data from X-ray images. The proposal, that the technique of "signature analysis" (as used in the examination of engineering structures) be developed as a diagnostic tool for spinal abnormalities was being investigated using these animal models. This paper emphasized the desirability of developing accurate methods for determining positions from X-ray images, a problem that was also addressed in another paper (Gertzbein) at this Symposium.

The ninth paper (Sances) described tests to failure of spinal segments, by both direct compression and bending. Also given were the results of tests of the elastic characteristics of individual components of the spine, such as ligaments, vertebral bodies, and the intervertebral discs. The authors described a non-linear, finite-element model of the spinal unit based on their data, and its validation using simulated compressive loads.

An automatic fitting procedure which best matches the gross anatomical features of the human spine, the ideal seating arrangement, and the most-suitable ergonomic seat design is a desirable goal if postural muscle fatigue is to be substantially reduced. Such an approach was the subject of the tenth paper (Coblentz). A dynamic program algorithm was given, which, by its inherent nature, determined the best posture in the ergonomic sense of a simple articulated human model. This model was comprised of two end reference points with eight contained segments: the head, cervical spine, thoracic spine, lumbar spine, sacrum, thigh, lower leg, and foot. The algorithm estimated the best set of angles for the eight articulations on the basis of information concerning the two reference points. The eleventh paper (Coblentz) provided biosteriometrical data of various parameters that have been obtained in order to define the external curvature of the spine for normal standing, and upright and relaxed seating positions. What is required now is that this model (or other computer-aided models of seating posture) be tested with the biosteriometrical data for different and novel seat designs, such as those recommended in the twelfth paper (Mandal).

5.3 Response of Spine to Vibration

The author of Paper No. 13 (Sandover) argued the case for the need for better epidemiological data -- preferably from controlled prospective studies -- on the effects of vibration on health. In particular, he argued on the need for a framework in which fatigue-induced lumbar disc degeneration can be properly related to the level and duration of vibration exposure experienced.

Two papers scheduled for this session in the Symposium were not presented. These were Paper No. 14, which was to address active and passive models of the lumbar spine to whole-body vibration, and Paper No. 15, which was to discuss the role of facets in wave propagation in the spine.

The response of the spine to vibration is usually measured with accelerometers, which are placed on the head or on some part of the trunk surface. The authors of the sixteenth and seventeenth papers reported results in which the transmissibility of sinusoidal vibration in the spine was measured with accelerometers attached to percutaneously-inserted Kirschner-wires ("K-wires") that were directly fastened to the spinous processes of the vertebrae. In the first of these two papers (Hagena), subjects with normal spines were exposed to sinusoidal Gz-vibrations at an acceleration of 0.2 g over the frequency range from 3 to 40 Hz. The uniaxial acceleration measurements identified three in-vivo responses of the human spine; one centered at 4-5 Hz (corresponding to the natural frequency of the whole body), another between 7 and 10 Hz for the spine, and one at about 18 Hz for the head. An interesting observation was that the natural resiliency of the spine absorbs up to 40% of sacrally-induced vibrations at the head. Furthermore, in-vitro tests on surgically-fused L4-L5 segments have shown increased amplitude vibrations in the neighbouring segments. This implies that personnel with ankylosing spondylitis or any similar pathology would experience greater than normal spinal segment stresses in a vibrational environment. This could lead to additional degenerative changes in the spine in such cases. In the second of these papers (Andersson), the results of experiments with healthy seated volunteers, who were exposed to vertical sinusoidal vibrations at accelerations of 0.1 and 0.3 g, over the frequency range from 2 to 15 Hz were discussed. Vibration measurements were taken at L1, L3 and at the sacrum, by means of transducer packages which simultaneously measured accelerations in three principal directions in the sagittal plane. Results showed that not only vertical, but also horizontal and rotary vibrations are induced in the vertebrae by vertical sinusoidal input accelerations. This has important implications if good ergonomic seating and anti-vibration practices are to be considered in any future cockpit developments. Resonance frequencies of the spine were 4.5 Hz in the vertical direction, and 4.5 Hz (possibly) for the rotary component. If there are horizontal resonances, then they are outside the range 0 to 15 Hz.

The eighteenth paper (Pellieux) described the development of a technique of great potential value in obtaining data relevant to biomechanical models. In theory, if one knows the linear transfer function which relates the motion of an arbitrary vertebra in a living animal to the motion of the seat on which the animal is placed, it should be possible to drive the vibrator to which the seat is attached (input) in such a way that the motion of the vertebra follows an arbitrarily-selected pattern (output). This would allow the study of the transfer function, which relates the motion of this vertebra to the motion of other vertebrae in the spine, to be conducted in the intact animal, rather than with excised specimens. The authors have worked towards this possibility, and have outlined the limitations of the technique imposed by the non-linearities and time dependence of biological systems, and the inherent limitations of mechanical vibrators.

5.4 Back Pain: Diagnosis, Prediction, and Prevention

Paper No. 19 which was to discuss pathological changes in aircrew spinal columns, was not presented at the Symposium.

The twentieth paper (Gertzbein) described an elegant method for determining lumbar spinal segment instability. The method uses a computer and digitizer to determine the instantaneous centre of rotation of lumbar spinal segment motion from radiographs during full extension and flexion of the spine in a highly accurate, rapid and reproducible way. The normal intervertebral "joint" has motion comprised of both rotation and translation; i.e., there is no single centre of rotation. Indeed, the centre of rotation moves through a locus called a centrode, which is measured by dividing the entire range of motion into finite component arcs whose individual centres of rotation are measured. Centrodes in normal lumbar segments differ both qualitatively and quantitatively from those in discs with degenerative diseases. In a sample of cadaveric spines, 94% of abnormal L4-L5 segements were detected with the new technique compared to only 25% with the standard flexion/extension radiographic technique for measuring excessive spinal segment motion. The method is currently being evaluated on normal volunteers. It promises to be useful in the early diagnosis of spinal segement instability (even before there are obvious radiographic changes) without having to resort to the stressful effects of discography.

The problem of choosing the best method for screening military recruits in order to reduce the incidence (and cost) of back pain and related disabilities in the armed services was addressed in two papers from Sweden, Nos. 21 and 22. The first of these (Nordgren) described the evaluation of a group of older men (mean age 37 years) who reported for refresher training; while the second (Hellsing) reported an evaluation of young men (mean age 18 years) during their first enlistment. In the Nordgren paper, it was found that those who had experienced back pain during service had significantly lower isometric strength in the abdominal and lower back muscles than others in the test group. The two papers gave apparently contradictory results: among young men, a history of back pain has more value than physical tests in predicting back problems during service; whereas, in older men, the physical test is the better predictor. This is probably because older persons will almost always have some back pain in their history, but, in younger persons, back pain is an unusual problem.

The twenty-third paper (Warrington-Kearsley) addressed the subtantial effectiveness that a structured back care programme can have in preventing low back pain from worsening or recurring. Interestingly, patients with long-standing low back pain displayed a characteristic weakness in their postural muscles during exercise training. This supports the view that most back pain arises from mechanical stress, either from muscular weakness or bad posture. Many of the author's data sample of trade-related back injuries were from military occupational categories that took awkward materials-handling positions (e.g., cooks), or else occupied inappropriate working postures (e.g., tank crewmen). Without preventative education, the majority of first-time sufferers can be expected to experience progressively debilitating, recurring episodes of back pain. However, experience with the Back Care Education Programme (BCEP) has now shown that over 70% of first-time patients required no further treatment following a structured program of education that was accompanied with a suitable regimen of prophylaxis. The current one-day (7 hour) BCEP emphasizes basic spinal anatomy and physiology, the biomechanics of spinal function, the psychological conditioning to chronic pain, and lifestyle changes and techniques which alleviate symptoms and reduce recurrent episodes of low back pain. The BCEP is well justified through cost effectiveness.

5.5 Back Discomfort: Cockpit Environment and Remedial Measures

The twenty-fourth paper (Bowden) noted that the postural muscle fatigue which results from maintaining an awkward working posture in flying the helicopter can be measured and quantified by electromyographic (EMG) methods. By appropriately relating muscle activity and fatigue, it may be possible to design cockpit environments with more suitable ergonomic conditions for relieving backache and back discomfort (e.g., through the use of side arm controllers, or vibration-attenuating seats, etc.).

In the twenty-fifth paper (Pope), erector spinae muscle EMG activity from the L3-segment level and subjective discomfort responses were used to assess back discomfort and muscle fatigue to both static posture and vibration exposure in a UH-1H helicopter cockpit mock-up. The study, which was based on a two-hour "flight", concluded that low-back and buttock discomfort appear to result from the UH-1H helicopter seating rather than the actual vibration. A surprise finding was that subjects reported less discomfort during UH-1H simulated vibration than during exposure for two hours to the static UH-1H seating environment.

The twenty-sixth paper (Poirier) identified posture and vibration as the causes of backache. The investigation into posture was carried out by the radiography of subjects sitting in mock-ups of selected helicopter cockpit seats. Several angles between body segments and spinal segments were measured. The results were presented as qualitative descriptions of the posture in the seats of three helicopters, the Alouette III, the Gazelle, and the Puma. The studies of vibration consisted of evaluations of the attenuation of vibration by various seat cushion foam materials. The authors noted that vibration in the vertical direction leads to a response in the horizontal direction in the upper body and head. This is consistent with the in-vivo observations of Gz vibrations in intervertebral segments related in the seventeenth paper (Andersson). While acknowledging that the effects of vibration on the spine are not yet well understood, the authors also noted the requirement for muscular contractions to resist the effects of vibration, and the consequent possibility of fatigue. The suggestion was made that any failure of the muscular damping of vibration could lead to clinical problems, since excessive loads would then be borne by the discs and ligaments. The paper noted the desirability of vibration reduction and improvements in the seat which would permit better posture. However, the hypothesis that helicopter vibration has a direct pathogenic effect on the spine was not given any supporting evidence.

The description of vibrational motion in three dimensions is often difficult to grasp conceptually. The twenty-seventh paper (Petternella) described an elegant method for representing the time-course of actual measured vibrations from a helicopter seat as a map derived from a two-dimensional Flamsteed projection of the unit sphere. The map shows clearly the presence of the principal rotational and translational vibration components. In order to allow the comparison of different vibrational environments, the coordinate axes can be chosen so that all of the translational motion is in the Z-axis, and the rotational motion is in the Y-Z plane. Frequency analysis of these separate components, rather than of the individual X, Y and Z components, yielded insight into the pattern of seat vibration, its causes and possible effects.

The twenty-eighth paper (Troup) proposed the use of precise (to 1 mm) measurements of body height (stature) as a means of estimating the cumulative effect of loads on the spine arising from occupational or postural stresses. The author cited reports in which the effects of running, lifting and pushing were studied. A notable finding was that differences in the loss of height correlated with the perceived exertion and discomfort. This suggests that the method could be used to measure the stresses which cause perceived back pain in various occupations. The method thus has potential for studies of the effects of various postures and vibration on drivers and pilots, but the author observed that its use as a tool in occupational medicine requires further study.

Papers Nos. 29 and 30 gave the results of incorporating seat re-designs, lumbar supports, improved seat cushions, and higher harness take-off points in cockpits as a means of relieving backache and back discomfort in flight. The author of the first of these papers (Reader) asserted that aircrew backache is caused solely by the sitting posture and the design of the seat. In support of this assertion, he provided statistics which showed that almost all fixed-wing and helicopter aircrew were either symptom-free or reported "considerably less" backache when using a lumbar support that restores normal lumbar lordosis during flight. Although these supports must be moulded to the contours of each wearer's back, they are simple in design, cheap, and easy to use. The author also noted that backache is consideraby reduced in new ejection seats and helicopter crew seats which incorporate lumbar support curves in their design. The second of the these papers (Braithwaite) discussed the improved comfort that Gazelle helicopter aircrew experienced because of seat modifications, new more-compliant seat cushions, lumbar supports, and harness assembly alterations. All of these modifications were directed towards removing those back stressors that resulted from poor seating posture.

The thirty-first paper (van Vliet) started from the premise that, given that poor posture and excessive vibration induce fatigue and discomfort in helicopter aircrew, can remedial measures be taken to alleviate these conditions? In order to reduce the vibrations that typically affect helicopter pilots, the authors suggested the use of active anti-vibrational seat-pan and seat-back cushions which adjust automatically to compensate for vehicle vibration, thereby keeping the pilot in a neutral position. (Each cushion is comprised of a matrix of four inflatable/deflatable air cells which are individually activated by air bellows that are responsive to feedback signals from aircraft motion-sensor inputs.) In initial tests, the prototype system has shown good isolation characteristics for the frequency range from 3 to 8 Hz. The system can be retrofitted in a variety of land and air vehicles. These authors also endorsed the use of side-arm displacement controllers, which are incorporated in a full-authority, fly-by-wire control system, to reduce the slumped and asymmetrical loading that pilots experience in current helicopter operations. More concrete results of these developments are now required.

6. CONCLUSIONS

6.1 Low-back pain, which is one of the most common ailments in modern society, is now being studied in particular detail. Papers were presented, from both the military and the construction industry, that addressed drivers' back pain from the points of view of the vibration exposure, the seating environment, and the medical consequences.

6.2 Helicopter pilots and fighter aircraft pilots both suffer low-back pain, but with different time-courses and with different severities. Are they the result of different biomechanical stresses? Perhaps; it could be that the severe accelerations of nap-of-the-earth flight or air combat maneuvers in fighter pilots produce the same effect as the violent lurching of off-road vehicles.

6.3 Because the helicopter pilot must assume a constrained posture while flying his vehicle, he is exposed to a milder, but constant, stress. Thus, his back pains are more common, but not as severe. Most can be relieved simply by rest. The more serious

problem is that the pain has induced some helicopter aircrew either to hurry their missions, or to refuse them. Therefore, it might be prudent, for the sake of mission safety and effectiveness, for field commanders to limit the length of helicopter missions.

6.4 The effective implementation of good seating procedures can be enhanced through efficient computer-aided methods which best match the gross anatomical features of the human spine, the ideal seating arrangement, and the most suitable ergonomic seat design. These methods should then be tested with biostereometrical and biomechanical data against different seat designs and cockpit environments. At the same time, a suitable measure of back stress, such as the change in stature, should be implemented as an index of pending back discomfort during workload, with and without vibration, in these different seating environments.

6.5 Attempts should be made to combine standardized data gathering methods with controlled prospective epidemiological investigations, in order to assess chronic low-back pain in vehicular drivers. Factors such as workload, the vibrational environment, seating posture, change in stature, etc., should be considered in the methodology.

6.6 Methods in which the accelerometers measuring the response of the spine to vibration are attached directly to the lumbar vertebrae (instead of to the head or trunk of the subject) promise to provide useful data on the transmission characteristics of the spine. The important finding that vertical vibration applied to the body produces vibrational motion in the lumbar spine that has not only vertical, but also horizontal and rotary components, has important implications, if good ergonomic seating and anti-vibration systems practices are to be considered in any future cockpit development.

6.7 Any method that reduces radiation exposure and the harmful effects of discography in the early diagnosis of spinal segment degeneration must be given serious consideration. Accordingly, the computer-aided method being developed by the team from Sunnybrook Medical Centre, Canada, for detecting instabilities in lumbar spinal segments deserves particular attention.

6.8 Methods for evaluating and predicting back pain in servicemen look promising but require further study.

6.9 The fact that over 70% of first-time patients require no further treatment when a structured program of back care education is followed with an accompanied regimen of prophylaxis, suggests that such a program is well justified in terms of cost effectiveness.

6.10 The method of measuring changes in stature should be investigated further for its potential as an index of accumulated back stress in the design of cockpit environments.

6.11 Flamsteed projections are well suited for representing the course of time-varying phenomena such as helicopter seat vibrations in two-dimensional space. The method should be further explored.

6.12 Modifications in seat configurations, improved seat cushions, individually-moulded lumbar supports, and higher restraint-harness take-off points are some of the retrofit concepts which should be implemented in current helicopter aircraft to improve pilot comfort.

6.13 The use of active anti-vibration seat-pan and seat-back cushions for attenuating the dominant vibration amplitudes is a practical approach for those vehicles that operate in environments of excessive vibration.

6.14 Perhaps the ideal system for reducing the backache/back-discomfort problem in helicopter cockpit environments is one that includes side-arm displacement controllers. These are incorporated in a full-authority fly-by-wire control system which avoids the necessity for the slouched and stressful posture required in current helico 'r cockpits.

7. RECOMMENDATIONS

7.1 The practice of including a good representation from both military and civilian experts to address and discuss common problems such as back pain in operational environments should continue at other AGARD AMP Symposiums.

7.2 The AGARD AMP should closely follow, and, where possible, influence the direction of new technological developments which emphasize sound ergonomic practices in advanced cockpit designs that will make aircraft less stressful to fly.

7.3 Although low-back ache is more closely associated with helicopter flight regimes than those with fixed-wing aircraft, cervical spine problems also appear to be within the domain of the fighter pilot. With the introduction of new high performance aircraft into NATO Forces, such as the F-16, F-18, Mirage 2000, and Tornado, with their unconventional flight regimes, neck injuries are expected to increase dramatically. Thus, there is a need for a future AGARD Specialists' Symposium that will address the topic of neck conditioning and neck-injury protection in advanced cockpit environments.

8. ACKNOWLEDGEMENTS

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EPIDEMIOLOGY OF THE DRIVER'S BACK

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Summary

Back pain is one of the most prevalent of modern symptoms and backache which comes on after sitting is a typical complaint, particularly amongst drivers. But drivers' backache is not confined to those who seek treatment: it is common throughout the population whether patients or non-patients. Yet both the aetiology and the pathomechanism remain unknown. Symptoms are related to the time spent at the wheel thus it may be inferred that they arise from the concomitant postural restraints. But static stresses in the spine arise both from the seated posture itself and from the muscular work of driving; while dynamic stresses, including vibration, arise from the motion of the vehicle. The epidemiological studies so far have not differentiated between the potential causative factors and few, if any, have taken account of other physical activities undertaken by drivers.

Introduction

Because drivers' back pain does not generally persist for long after alighting, it has not been studied clinically. Nevertheless it can be postulated that, in its commoner forms, it is a primary back pain arising directly from the tissues of the spine: skin, muscle, fascia, ligaments, periosteum, the capsules of the apophyseal joints, the adventitia of blood vessels or the spinal meninges. None of these sites can be excluded. The sites which are unlikely sources of pain, however, are those which are not normally innervated: the discs, epiphyseal plates and the cartilaginous facets of the apophyseal joints.

It is conceivable that a mechanical irritation of the more superficial of spinal tissues can arise from the variation in the contact between the driver's back and the backrest of the seat: analogous to the discomfort in the buttocks and under the thighs due to prolonged tissue compression, aggravated by the motion of the vehicle; though without the associated risks of ischaemia. The frame of the seat moves with the vehicle and the driver's movements follow. The time lag between the two patterns of motion results in interactive forces that vary with the softness of the upholstery; but also with the physical characteristics of the seat springs, which may lead either to amplification or attenuation of the mechanical input.

The compressive load on the spine is a function of the static and dynamic components. The force of gravity on the upper part of the body is transmitted wholly by the lumbar vertebrae and discs if the back is unsupported. Part of the vertical load is transmitted by the backrest, depending on its inclination to the vertical and on the area of contact with the body, but also on the contour of the backrest and the level of the spine at which load transmission occurs. Andersson et al. (1975) found that support in the back rest at the level of L3 was the most effective. The static load on the spine stems also from muscular activity and this can vary considerably, according to the type of vehicle being driven and to the postural behaviour of the driver. The controls demand muscular effort at hands and feet which in turn requires reactive postural activity from the muscles of the trunk, so increasing the static load. The driver's posture itself depends primarily on the visual constraints but also on the layout of the controls. If weather conditions are poor and the driver fatigued, the driving position is liable to change and the static muscle load to increase, particularly when the driver ceases to lean back on the backrest. Postural back muscle tension, while adding to the static spinal load, may itself cause symptoms.

The dynamic component of lumbosacral compression depends on the ride characteristics of the vehicle, its changes in speed and direction and on the surface being traversed (Troup 1978; Sandover 1981). The problems arise when the driver's body is oscillated at its natural frequency of 4 to 8 Hz, and this is highly probable in some trucks operated on rough ground; or, when going over stones, ruts and potholes, the body is subjected to vertical or verticolateral impacts. The two problems tend to coincide in practice. The latter may be potentially traumatic but it is theoretically possible for fatigue failure to occur as a result of the combined effects of the vibration and repeated impacts or shocks. But this would probably be limited to those already in pain. Trauma would be most likely in the weight bearing tissues which are normally not innervated and thus likely to be the sites of the immediate pain that drivers commonly experience.

If the combination of static and dynamic compressive loading is prolonged then creep-effects may supervene. Creep-effects occur whenever the compressive load on the disc exceeds the interstitial osmotic pressure, whereupon fluid is expelled; and these effects are accelerated when vibratory input is added to the static compressive load (Kazarian 1972, 1975). The disc becomes narrowed and stiffened and the dynamic response characteristics of the intervertebral joint complex undergo marked changes, one of the consequences being a lowered threshold of resistance to failure. Nothing, however, appears to be known of any direct relation between the results of such creep-effects and symptoms.

An additional factor which the epidemiologist must bear in mind is the activity of the driver before and after being in the driving seat. Many professional drivers have relatively heavy manual handling tasks to perform which may in turn influence the symptoms associated with driving.

The hypothetical causes of drivers' backache are limited to a mechanical irritation arising from the interaction between the driver's back and the backrest; to postural stress leading to static, hypertensive muscle pain; to the cumulative effects of the vibratory inputs plus the impact shocks; or to aggravation of existing symptoms. Thus the temporal pattern of the driver's symptoms, the previous history of lumbar spinal disorders, the design and layout of the driving position, the driver's postural behaviour, the ride characteristics of the vehicle and the nature of the surfaces it traverses are all relevant to the epidemiologist.

Epidemiological Studies

Driving has been listed in a number of studies as one of the many aggravating factors listed by patients with back pain (Kelsey 1975a,b; Buckle et al. 1980; Frymoyer et al. 1983; Damkot et al. 1984). Driving itself, though, was not their main focus of interest. Kelsey & Hardy (1975) undertook a clinical epidemiological study and identified three groups of patients as confirmed, probable or possible cases of herniated disc prolapse and compared them with two groups of patients to serve as controls. They found that the men who spent more than half their working hours at the wheel were three times as likely to have a prolapsed intervertebral disc. Buckle et al. (1980) studied the occupational factors involved in 68 male back pain patients requiring hospital treatment, and found that the 70% of them who were drivers averaged 16,754 miles compared with the national average of 9,000. Thus there is reliable evidence that in patients with established back pain for which they sought hospital treatment, driving was a contributory aetiological factor. But in neither study was there any differentiation between the types of vehicle driven.

Milby & Spear (1974) reported on the back pain and other symptoms reported by heavy equipment operators exposed to substantial vibratory stress and impact-shock but considered that the adverse effects of vibration, which they had predicted, were concealed by the fact that many of those who were so affected had moved to other jobs. Gruber (1976) studied "vertebrogenic pain syndromes" in 4,353 male drivers and 736 controls aged 35 to 54 years. The drivers included 1,099 truck drivers engaged in local delivery, 1,266 long distance truck drivers and 1,988 bus drivers. The control subjects were air traffic controllers: a sedentary job but with a different level of decision-making. The incidence of "vertebrogenic pain syndromes" in the controls was not significantly less than in the long distance truck drivers but both groups of truck drivers reported more symptoms than the bus drivers. But this was a retrospective clinical study in which unconfirmed diagnoses had been classified, allegedly according to the ICDA codes but with degenerative deformations of the spine (713.1) classed with "bone deformities" (735-738). Thus no clear deductions could be drawn about the aetiological role of either driving itself or the effects of vehicle vibration.

More recently in Finland, a cross-sectional health survey was made of 633 male drivers during the winter of 1979/1980 (Backman 1983). 165 were local bus-drivers, 122 long distance bus-drivers, 154 stock delivery drivers, 159 truck drivers and 33 were tank-truck drivers. The incidence of complaints of pain in the shoulders, neck and back increased with age. 40% of all drivers "often had back trouble", though it was commonest in the bus drivers. Reporting on the same population, Backman et al. (1982) noted that in the year prior to the study 64% of all drivers had experienced some back trouble, prevalences of back and sciatic pain again being higher in bus drivers, but absence from work due to back pain was commoner in the stock delivery drivers.

Job-turnover in professional drivers was studied in 1979 in a cohort of 1,453 males who had joined their trade union from 1967 to 1969 and who lived in six urban municipalities in Finland (Backman & Järvinen 1983). 1,156 (80%) responded and 69% of the responders were still employed as drivers while 24% had changed to another job and 7% had retired. "Salary" and "heaviness of work" were the commonest reasons for changing jobs. The commonest change was to driving buses, particularly amongst the younger drivers while the older ones tended to change to truck driving, especially sand and gravel transport. Of the 66 drivers who retired because of illness or accidents, in 18 cases the reason given was back pain.

Discussion

The epidemiological evidence of any causal relation between driving and back pain remains slender. The strongest evidence concerns patients with back pain of a severity to warrant treatment at a hospital: a small proportion of the total population. Nonetheless, the fact that such patients were found to drive, on average, significantly more than other people indicates that driving may have contributed to their back pain.

But without prospective epidemiological studies some doubts must remain. There appears to be no evidence whatever of driving as a primary cause of back pain, except as a result of road traffic accidents. Backman (1983) did, in fact, report that 33% of drivers in the cross-sectional health survey had been involved in accidents but had given no information about the injuries sustained.

The two surveys of drivers in the USA throw little light on the subject; though Milby & Spear (1974) did recognize the need in future studies to take account of the drivers who had left their jobs and of the reasons for so doing. The Finnish survey of the reasons for having to change jobs (Backman & Järvinen 1983) did not identify sand and gravel transport as a particular risk for back pain although it might be thought that, at least within the territory of the sand and gravel quarries or the delivery-sites, ride-characteristics would be bad. On the contrary, the middle aged drivers who changed jobs often chose this work because, the authors suggested, the operation was generally automatic and entailed little physical exertion. It may well be that the number of drivers who change jobs because of back pain reflects the occurrence of back morbidity in the population rather than a causal link. Moreover, those with back trouble would be likely to find that the manual work associated with driving was the problem rather than the driving itself.

The contributory role of vibration and the shock of impact from bad road surfaces remains unclear. None of the epidemiological studies seen so far have incorporated the relevant data on occupational exposure. It remains theoretically possible that subjection to severe vibration and road shock may have a cumulative effect in increasing the susceptibility to injury but hard evidence is still wanted.

Conclusion

For lack of better evidence, back pain when driving can be classified in two ways. In patients who have sought treatment for their pain and in whom the cause has been diagnosed as, for example, herniated lumbar disc; driving is likely to exacerbate the symptoms and may, conceivably, have contributed to the severity of the condition. In the second group of otherwise healthy people who experience back pain while driving and in whom symptoms are relieved soon after alighting from the vehicle, the most likely cause of pain is postural hypertension of the back muscles, though this remains to be investigated.

Prevention of symptoms in the second group can be approached ergonomically and the ergonomic solutions would make driving more acceptable to the first group. Although defensible epidemiological evidence for the adverse effects of severe vibration and road-shock is still awaited, already a number of ergonomic solutions to the problem have been proposed and, judging by the reduced levels of discomfort which have been achieved, this is a reasonable approach. In theory, prevention of injuries and accidents should be cost-effective and there are substantial cost benefits to be gained from elimination of occupationally induced musculoskeletal pain by ergonomic redesign. If a vehicle is badly designed and a source of driver-pain, medical costs may arise from treating the driver but additionally, the cost may be measurable in terms of job-turnover and the expense of training the replacements. Possibly, given a large enough driver-population, the quality of vehicle design may be reflected in the incidence of accidents and near-accidents or in other measures of driving skill.

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DISCUSSION

LANDOLT, CH: *How important is vibration in the genesis of backache?*

TROUP, UK: The answer is that I don't know, and I am really very unhappy about the epidemiological evidence, mainly because it is not controlled (most of it) for the other tasks which drivers do. Vibration on roads, on the whole, is not serious; but vibration off the road -- on farms, in forests, and on construction sites -- certainly does expose the driver to possible minor trauma and accumulative effects, such as creep effects in the spine, and the stiffening and the greater susceptibility to injury which these inputs generate. My general feeling, speaking as a clinician as well as a biomechanic, is that it is off-the-road driving, on seriously uneven ground, on which the body is jolted sideways, backwards and forwards, that is the real problem.

Relationships between whole-body vibration and disorders of the backbone diagnosed on operators of earth-moving machinery

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Summary:

The study based on interviewing 352 operators of earth-moving machinery who had been exposed to whole-body vibration for at least 3 years. A further examination dealt with the evaluation of available X-rays showing different parts of the spines of 251 machinery operators who had been exposed to vibration for at least 10 years.

The discomfort most often mentioned was impairment of health and well-beeing during and after the working shift (mentioned by 75 % and 59 % respectively). Apart from that, the percentage of subjects complaining about spinal discomforts was much higher for the exposed group than for the non-exposed group (70 % and 54 % respectively).

The epidemiologic study resulted in an objective confirmation of the spinal discomforts indicated, 2/3 of which had been related by the operators to the lumbar spine. Of all disorders diagnosed for the operators, the lumbar syndrome accounted for the greatest share by far 81 %.

In three cases, diagnosis for the operators was "avulsion fracture of the spinous processus of a vertebral body in the cervical column".

The frequency distribution resulting from the radiographic examination of 251 earth-moving machinery operators with at least a 10 years' exposure to whole-body vibration showed that morphological changes in the lumbar spine occur earlier and much more frequently than in the case of non-exposed persons.

Introduction:

Driving and operating earth-movers gives to regular mechanical vibration which is received by the operator as whole-body vibration. For the different types of machinery (wheel-type, track-type), the mean frequency ranges from 1.5 to 10 Hz. The vertical mechanical vibration reaches the exposed person's body by way of the buttocks.

Since there is a lack of reliable knowledge in the field of occupational medicine, particularly with regard to lasting disorders of health suffered by peple exposed to whole-body vibration during work, we carried out a large-scale epidemiologic study in order to try to identify vibration-induces disorders of health.

The study based on interviewing 352 operators of earth-moving machinery who had been exposed to whole-body vibration for at least 3 years. Additional information was obtained from objective medical evidence relating to the persons exposed. A further examination dealt with the evaluation of available X-rays showing different parts of the spines of 251 machinery operators who had been exposed to vibration for at least 10 years.

In a further study, 149 operators of earth-moving machines were questioned about their subjective well-being immediately after the working shift. [1,2]

Results:

Subjective well-being

The results of the enquries among the 352 operators of earth-moving machines and the control group (Figure 1) indicate that a comparatively high proportion of those exposed to vibration reported a disturbance in their health or well-being during and after the shift and also spine-related discomfort.

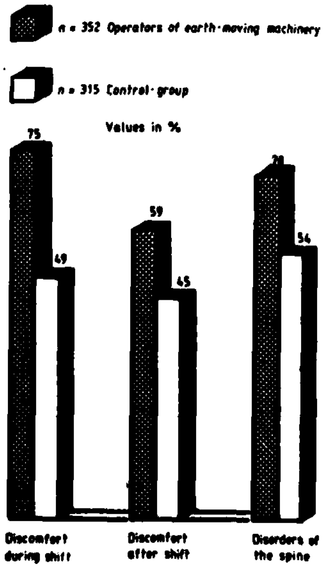
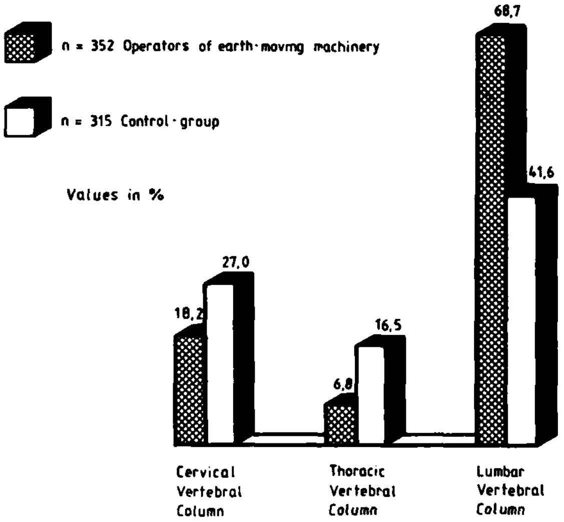


Figure 1:

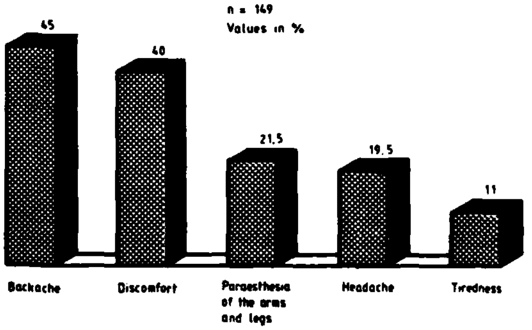
The localisation of the discomfort to individual segments of the spine by the machine operators questioned is illustrated in Figure 2. This graphic presentation shows clearly that the lumbar spine has a far higher "sensitivity" to whole-body vibration stresses than other segments of the spine when the mechanical vibrations are transmitted to the body via the buttocks. In the control group, the proportion of persons reporting discomfort in the area of the cervical and thoracic spinal column was actually higher than in the group exposed to vibration.

Figure 2:
Comparison of discomforts in the area of individual segments of the spinal column between operators of earth moving machines and the control group



The aim of questioning the 149 operators of earth moving machines immediately after an eight hour shift was primarily to discover any discomforts which could be casually related to exposure to whole-body vibration. The attempt to assign discomfort to specific types of earth-moving machine proved to be infeasible as the operators of the earth-moving machines in this team operated various types of earth-moving machine alternately during their shift. As Figure 3 shows, "back pains" (45 %) was the discomfort most frequently reported.

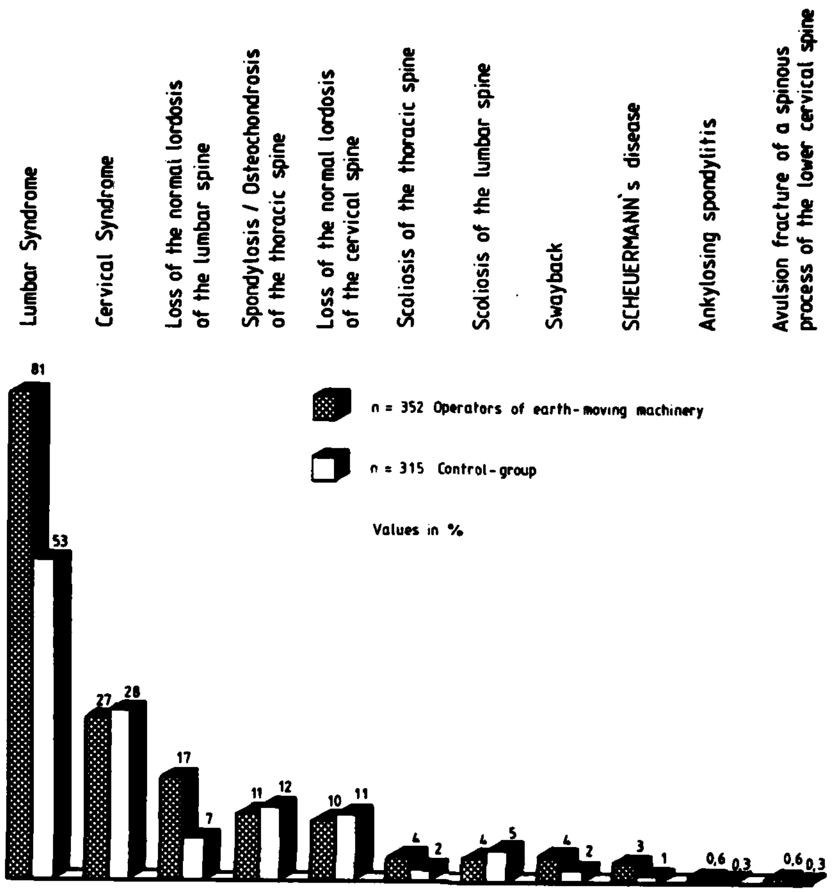
Figure 3:
Questioning of operators of earth-moving machines about discomfort immediately after exposure to whole-body vibrations for eight hours



A differentiation of the operators of earth-moving machines into those primarily operating wheel-mounted machines and those operating crawler-mounted machines revealed no appreciable difference in the frequency of back pains reported. The only noticeable difference was that in the group of crawler-mounted machine operators, paresthesia of the limbs occurred considerably more frequently (wheel-mounted machine operators 18 %, crawler-mounted machine operators 28 %).

Clinical results and X-ray findings
The comparative presentation in Figure 4 takes into consideration only such pains and discomforts for which a causal relationship with the whole-body vibration load was conceivable.
Lumbar syndrome, with 81 %, was the primary cause of health impairment among the operators of earth-moving machines. Among the workers of the control collective not exposed to vibration, on the other hand, this diagnosis was found in only 53 % of cases.
The diagnosis "lumbar syndrome" covers all the symptoms which are caused directly or indirectly by degenerative lesions of the lumbar disks.

Figure 4:



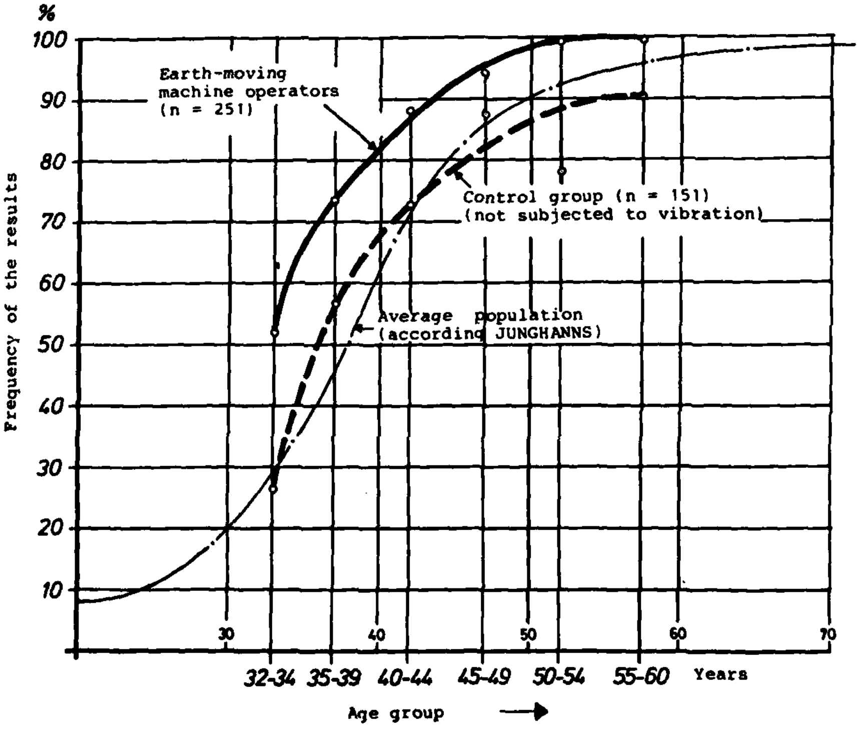
These include, in particular, spondylosis of the lumbar column (disk degeneration with reactive spurring at the edges of the spine), spondylarthrosis of the lumbar spine (degenerative changes in the spinal column, generally due to disk degeneration) and the spondylochondrosis of the lumbar spine (disk degeneration involving the adjoining upper and lower plates of the vertebral body), insofar as these lesions had led to radiologically demonstrable morphological changes in the spinal column, and were associated with disk-related complaints (pains or functional disturbances of the lumbar spine). Clinical symptoms such as ischialgia (lumbar syndrome involving the sciatic nerve) and lumbago (acute form of lumbar syndrome) were also included. Spondylolisthesis was also included under lumbar syndrome.

The occupational load on the operators of the earth-moving machines caused by mechanical vibrations appears to cause a considerably smaller strain on the cervical column, since the number of cases of cervical syndrome in the group of earth-moving machine operators and the control group was equally high. Three persons in the group of earth-moving machine operators received the remarkable diagnosis "avulsion fracture of the spinous process of a vertebra in the cervical column" (see Figure 5). This diagnosis of damage to the cervical column was confirmed by X-ray.

Figure 5:
Avulsion fracture of the spinous process of the 7th thoracic vertebra in an earth-moving machine operator as a result of whole-body vibration loads

A similar statement can be made for the results of examinations in the area of the thoracic column.
Figure 6 shows the radiologically proven morphological changes in the lumbar spine as a function of age.

Figure 6:
Radiologically demonstrable morphological changes in the lumbar spine (wear) on earth-moving machine operators with at least 10 years exposure to whole-body vibrations and of a control group not exposed to vibration loads (distribution according to age groups). The results are compared with the "morphological results" of the thoracic and cervical columns of average population as studied by JUNGHANNS (1931) [3]



The differences between the frequency of pathological results for the operators of earth-moving machines and for the control group are statistically significant at the 0,1 % level.
These results were compared with the morphological results for the spine among the average population according to Junghanns (1931).[3]
The values for our control group evidently coincide very well eith the values for the average population in Junghanns. In contrast, the radiologically proven changes to the lumbar spine of the earth-moving machine operators examined by us occurred prematurely and more frequently.

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DISCUSSION

LANDOLT, CA: In what way is your control group comparable to the vibration-exposed group? For instance, did your control group take similar seating postures to your machine operators?

ZERLETT, GE: For the control group of non-exposed people, it was guaranteed that there was no exposure to whole-body vibration. The average age of the exposed people was about 42 years, and the age distribution was similar in both groups. I cannot say that the seat posture was identical in all cases; but I can say that most of the subjects took a similar seating posture.

L'ENVIRONNEMENT VIBRATOIRE AU POSTE DE CONDUITE DES ENGINS DE TERRASSEMENT

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France

RESUME : Des mesures, effectuées en collaboration avec des constructeurs et des utilisateurs d'engins de terrassement, ont permis à l'I.N.R.S. d'une part de dresser un bilan de la contrainte vibratoire au poste de conduite d'environ 70 engins de terrassement différents, actuellement utilisés en France, d'autre part d'évaluer l'efficacité des suspensions des sièges qui les équipent. Les mesures d'accélération ont été effectuées sur l'assise du siège et à sa base de fixation, selon trois axes orthonormés. Plus de 150 essais ont été réalisés pour avoir un échantillonnage complet des principales tâches que peuvent effectuer les véhicules concernés. D'après la norme AFNOR NF E 90-401, les contraintes vibratoires globales rencontrées pour les véhicules montés sur pneumatiques en phase de roulement (tombereaux et camions tous chemins, décapeuses automotrices, chariots automoteurs, etc...) sont globalement plus sévères que celles trouvées pour les pelles hydrauliques et chargeuses-pelleteuses, lors du creusement de tranchées. Si l'on excepte les véhicules effectuant des tâches de creusement, reprise au tas ou rippage, les vibrations dirigées selon l'axe vertical sont généralement prédominantes. De plus, les résultats montrent que les suspensions verticales des sièges, équipant les véhicules testés, notamment ceux montés sur pneumatiques sont fréquemment inadaptées. Il y a donc lieu d'appliquer le code d'essais de sièges défini par la norme française AFNOR E 58-074 pour les engins de chantier. Les mesures effectuées à la base du siège ont permis dans l'ensemble, de valider la pertinence des classes spectrales des processus vibratoires préconisés par cette norme pour effectuer en laboratoire les essais de sièges bien que quelques modifications soient suggérées. En particulier, il est proposé d'inclure les tombereaux et camions de chantier et de créer deux nouvelles classes pour prendre en compte les vibrations horizontales lorsque celà s'avère nécessaire.

ABSTRACT : Measurements made with manufacturers and users enabled I.N.R.S. to evaluate the vibration exposure at the workplace of about 70 different off-road machines presently used in France and the efficiency of machine suspension seats. Measurements were obtained from accelerometers mounted triaxially, placed on the seat pan and on the floor beneath the seat. More than 150 runs were performed to consider a range of typical operating conditions of vehicles studied. According to the standard AFNOR NF E 90-401 the vibration exposures measured on running vehicles fitted with pneumatic tyres (dumpers and off-road trucks, tractor scrappers, off-road fork lift trucks, etc...) were greater than those recorded in excavators and back-hoe loaders while digging trenches. The drivers were exposed mainly to vertical vibration unless the vehicles were used for excavating or scraping. In addition, the results show how poor is the isolation provided by the seat vertical suspension systems which equipped the vehicles tested especially those fitted with pneumatic tyres. This proves the necessity to apply seat test code as defined by the French standard AFNOR E 58-074 for off-road machines. The measurements made on the floor beneath the seat generally validate the pertinence of input vibration spectral classes recommended by this standard to test seats in laboratory although some modification are suggested. Particularly, it is proposed to include the dumpers and off-road trucks and to define two new classes to take into account horizontal vibrations when necessary.

INTRODUCTION

La conduite d'engins de chantier concerne un nombre important de travailleurs puisqu'on peut estimer, rien que pour la France, le parc des engins à environ 150 000, parmi lesquels plus de 20 000 pelles hydrauliques, 40 000 chargeuses et chargeuses pelleteuses, 40 000 chariots élévateurs tous terrains, 5 000 tracteurs sur chenilles, etc. [1]. Les conducteurs sont astreints à des conditions de travail rendues souvent pénibles par les paramètres de l'environnement physique et les caractéristiques ergonomiques du poste de conduite, ce qui explique la désaffection observée pour ce métier avec l'ancienneté.

Cette constatation a amené l'I.N.R.S. à entreprendre l'étude des niveaux de bruit [2] et de vibrations [3] perçus au poste de conduite des engins de terrassement, en collaboration avec des constructeurs, des importateurs et des utilisateurs de matériel. Le présent article ne concerne que la partie vibration de cette étude.

Les vibrations transmises à l'ensemble du corps sont généralement considérées comme une cause de stress généralisé. En effet, il est difficile de définir des effets physiologiques chroniques précis car elles agissent simultanément sur de multiples organes. Ceci explique que l'on connaisse très mal les problèmes de santé qui affectent les personnes exposées. Une enquête effectuée par le NIOSH (Institut National de la Santé et de la Sécurité du Travail des Etats-Unis), portant sur 3 900 dossiers médicaux, a permis d'identifier chez les opérateurs d'engins les symptômes suivants : problèmes digestifs, génito-urinaires, intestinaux, affections d'ordre musculo-squelettique et cardiaque, tension au travail [4]. On notera néanmoins que l'augmentation du taux de morbidité observée dans la profession pour ces pathologies, n'est pas supérieure à celle constatée pour des travailleurs non exposés à des vibrations, du fait que la probabilité de quitter son emploi est plus forte pour des conducteurs malades que pour des travailleurs sédentaires atteints des mêmes symptômes [5].

Les travaux entrepris par l'I.N.R.S. pour améliorer l'hygiène au travail des conducteurs d'engins, sont basés sur l'a priori que la réduction de la contrainte vibratoire entrainera automatiquement la diminution de l'astreinte. L'intensité de la vibration peut être atténuée à différents étages : à la source (planéité des pistes...), au niveau de la suspension de la caisse (la plupart des véhicules tous-terrains ne sont pas encore pourvus de suspensions efficaces), des pneumatiques, de la suspension de la cabine et du siège [1 et 6]. Mais l'étage le plus important pour le préventeur, à l'heure actuelle, est celui constitué par le siège car :

- il représente l'ultime maillon qui sépare l'homme de la machine ;
- il est généralement le moins cher ;
- il est le seul sur lequel on peut pratiquement agir après la réalisation de l'engin.

C'est pourquoi, l'étude présentée dans cet article, vise les deux objectifs suivants :

(a) Comparer les contraintes vibratoires relevées au poste de conduite des principaux engins de chantier actuellement utilisés en France.

(b) Mesurer l'efficacité des suspensions des sièges équipant ces engins, dans des conditions réelles d'utilisation, et évaluer la pertinence des classes spectrales des vibrations d'excitation contenues dans le code d'essai de sièges d'engins de terrassement (norme française expérimentale E 58-074 [7].

1. MATERIEL ET METHODE

1.1. Matériel

1.1.1 Sélection des engins retenus pour la conduite de l'étude

Des discussions avec les professionnels ont débouché sur la sélection de 70 engins différents de façon à couvrir les types de machines les plus couramment utilisées sur les chantiers (pelles hydrauliques, bouteurs, chargeuses, chargeuses-pelleteuses, niveleuses, décapeuses automotrices, tombereaux, camions tous chemins, chariots élévateurs de chantier) parmi les marques et modèles diffusés en France (voir tableau 1). En dépit du nombre d'engins testés, l'étude ne prétend être ni exhaustive, ni représentative. Mais elle a le mérite de fournir une photographie vraisemblable du parc actuel français.

1.1.2. Définition des conditions d'utilisation

Il est bon de rappeler ici, la philosophie de la France en matière de code d'essai en vibration des sièges d'engins de chantier puisque cet aspect a fortement conditionné le plan expérimental de l'étude.

- Le siège doit avoir un comportement dynamique in situ satisfaisant dans tous les cas et plus particulièrement dans des conditions de sollicitations difficiles qui sont à l'origine des niveaux vibratoires les plus élevés.
- C'est pourquoi, on borne le problème par la sévérité vibratoire des tâches typiques retenues (il peut y en avoir plusieurs).
- Sous ces conditions, l'intensité des vibrations transmises par le séant au conducteur suivant l'axe séant-tête ne doit pas dépasser lors des essais, la valeur de 1,25 m/s^2 (cf. la norme française NF E 58-050 [8] et la directive européenne CEE L 255 [9], relative aux tracteurs agricoles). Il s'agit d'une valeur limite et non pas d'une valeur moyenne acceptable 8 heures par jour.
- Les essais sont effectués en laboratoire sur un simulateur de vibrations. La norme E 58-074 définit 4 classes spectrales de vibrations d'entrées verticales en fonction des espèces d'engins.

(a) Réglage des sièges.
On a vérifié que les sièges ne présentaient pas d'anomalie flagrante de fonctionnment statique et qu'ils étaient correctement fixés sur le plancher du poste de conduite. Lorsqu'ils étaient pourvus de réglages (poids, hauteur, longitudinal), les sièges étaient ajustés selon les préférences du conducteur, des précautions étant prises pour minimiser les risques de fonctionnement anormal en régime dynamique.

Engins	Nombre d'engins	Nombre de marques différentes	Tâches
Pelle hydraulique	19	6	creusement
Bouteur	11	5	rippage, décaissement, roulement
Chargeuse	13	8	roulement
Chargeuse-pelleteuse	7	4	reprise au tas, roulement
Niveleuse	4	3	nivellement
Décapeuse automotrice	2	2	décapage, roulement
Tombereau et camion tous chemins	6	4	roulement
Chariot tous terrains	8	4	roulement
TOTAL	70		

Tableau 1 - Répartition des engins testés

(b) Choix des cycles de travail.
A défaut de cycles de travail normalisés, les configurations expérimentales retenues ont été celles qui sont les plus représentatives des conditions réelles de travail (cf. tableau 1). Ainsi, pour les pelles hydrauliques, les phases de roulement n'ont pas été prises en considération. Les paramètres liés au site expérimental (relief, nature, granulométrie et dureté du sol, etc.) n'étant ni maîtrisables, ni aisément mesurables, il a été décidé de s'en tenir à la notion de "conditions courantes de chantiers" pour l'exécution des essais.

(c) Instructions données aux conducteurs.
Avant les essais, on a demandé aux conducteurs (les véhicules étaient conduits par les opérateurs habituels) :
- de maintenir un "rythme de travail soutenu et régulier", le but visé était d'obtenir, d'une part un régime vibratoire le plus stationnaire possible et d'autre part, un "majorant" de la contrainte vibratoire correspondant sensiblement à une journée normale de travail. Pour chaque configuration expérimentale, la durée des échantillons prélevés en régime stabilisé de vibrations était de l'ordre de 5 minutes ;
- d'éviter d'exciter le siège par actions brutales sur les commandes ou modifications posturales importantes.

1.2. Méthode

1.2.1. Mesure des vibrations

Les mesures de vibrations ont été réalisées, en application des normes internationales et françaises, relatives à l'évaluation de l'exposition des individus à des vibrations globales du corps (normes ISO 2631 [10] et AFNOR NF E 90-401 [11] et au code d'essai de sièges en vibration (normes AFNOR NF E 90-451 [12] et expérimentale E 58-074). Les mesures ont été prises :
- sur l'assise du siège au moyen d'une interface de mesure semi-rigide (contenant 3 accéléromètres Schlumberger CD 0223/S linéaires) placée entre la sellerie et le séant du conducteur sous les tubérosités ischiales ;
- à la base du siège au moyen de 3 accéléromètres linéaires similaires fixés à l'aide d'un aimant (ayant une force d'attraction d'environ 1 000 N) sur la partie rigide la plus proche de l'amarrage du siège sur le plancher de la cabine.

Les accéléromètres linéaires avaient leurs axes sensibles orientés selon un trièdre orthonormé :
- axe X : direction avant-arrière
- axe Y : direction latérale
- axe Z : direction verticale.

Les signaux analogiques correspondants ont été enregistrés sur bandes magnétiques pour être analysés en temps différé. Pour les véhicules évoluant au point fixe ou sur un très faible rayon d'action, les liaisons entre les chaînes de mesure et l'enregistreur ont été effectuées par câbles. Pour les autres engins, on a utilisé une télémesure ayant une bande passante de 0,1 à 250 Hz et dont la portée était d'environ 200 mètres en terrain découvert.

1.2.2. Calcul des valeurs caractéristiques.

Les enregistrements accélérométriques ont fait l'objet des dépouillements et calculs suivants :

(a) Spectres fréquentiels et courbes enveloppes. Les densités spectrales de puissance (D.S.P.) des accélérations mesurées sur l'assise du siège et sur le plancher ont été calculées sur un analyseur de Fourier GENRAD modèle GR 2506, à deux voies d'acquisition simultanées. Les échantillons d'une durée de 300 secondes ont été analysés dans la bande fréquentielle 0-80 Hz. La fréquence d'échantillonnage était de 205 Hz et le nombre de moyennes 60, ce qui a permis d'obtenir une résolution de 0,2 Hz. Il n'a pas été utilisé de fenêtre de Hanning.
En outre, pour chaque espèce d'engins et chaque tâche, on a regroupé les diverses D.S.P. des accélérations mesurées sur le plancher et on a calculé les courbes enveloppes maximales, moyennes et minimales correspondantes.

(b) Valeurs efficaces des accélérations linéaires pondérées et des accélérations équivalentes. La pondération fréquentielle, représentative des différences de sensibilité de l'homme aux vibrations en fonction de la fréquence et de la direction, a été effectuée au niveau des différentes D.S.P., des accélérations linéaires, conformément à la norme ISO 2631. Les valeurs efficaces des accélérations pondérées correspondantes (a_{wx}, a_{wy} et a_{wz}) ont été déduites par intégration de ces D.S.P. ainsi modifiées. L'accélération équivalente, au niveau de l'assise du siège, a été calculée à partir de la formule préconisée par la norme AFNOR NF E 90-401 :

$$a_{eq} = \sqrt{a_{wz}^2 + 2\ a_{wx}^2 + 2\ a_{wy}^2}$$

(c) Rapports de transmission vibratoire entre siège et plancher ou entre axes différents :
- L'évaluation de l'efficacité des systèmes antivibratiles des sièges selon l'axe vertical s'est faite au moyen du rapport suivant :

  $$R_z = \frac{a_{ws,z}}{a_{wp,z}}$$

  avec $a_{ws,z}$ et $a_{wp,z}$ correspondant respectivement aux accélérations efficaces pondérées selon l'axe z relevées au niveau de l'assise du siège et du plancher (cf. norme AFNOR NF E 90-451). Si R_z est supérieur à 1, on considère que le siège globalement amplifie ; par contre, si R_z est inférieur à 1, le siège atténue l'intensité vibratoire.
- Il était en outre intéressant de connaître la direction ou les directions privilégiées de vibrations. Pour celà, on a calculé, au niveau de l'assise du siège, le rapport $R_{s,iz}$ défini par la formule : $R_{s,iz} = \frac{\sqrt{2}\ a_{ws,i}}{a_{ws,z}}$ avec : i = X ou Y.

2. RESULTATS DES MESURES

Plus de 150 essais ont été effectués pour couvrir les différentes tâches que peuvent effectuer les 70 véhicules testés. Chaque essai a fait l'objet de deux fiches individuelles de résultats comportant des précisions pour chacun des engins testés, les valeurs des grandeurs citées dans le paragraphe 1.2.2 et les courbes de D.S.P. Les résultats présentés dans cet article constituent, pour l'essentiel, une synthèse de ces fiches.

2.1. Evaluation de la contrainte vibratoire au poste de conduite en référence à la norme ISO 2631.

(a) Accélération équivalente. La figure 1 montre que les intensités les plus sévères, relevées sur l'assise du siège, sont généralement rencontrées pour les véhicules montés sur pneumatiques en phase de roulement, la contrainte étant parfois incompatible avec la durée courante d'un poste de travail. En effet, des accélérations équivalentes de plus de 2 m/s^2 ont été trouvées sur 1 des 2 décapeuses, sur 4 des 6 tombereaux et camions de chantier et sur 5 des 8 chariots étudiés, ce qui n'autoriserait sous ces conditions que des temps d'exposition de moins de 2 heures, en référence à la norme française NF E 90-401. En moyenne, les niveaux mesurés sur les engins montés sur chenilles (chargeuses et bouteurs) sont de l'ordre de 1,2 m/s^2, quelle que soit la tâche effectuée (roulement, reprise au tas, etc.). Les contraintes vibratoires globales les plus faibles (environ 0,6 – 0,8 m/s^2) ont été obtenues pour les pelles hydrauliques et chargeuses-pelleteuses, lors du creusement de tranchées au point fixe et pour les niveleuses.

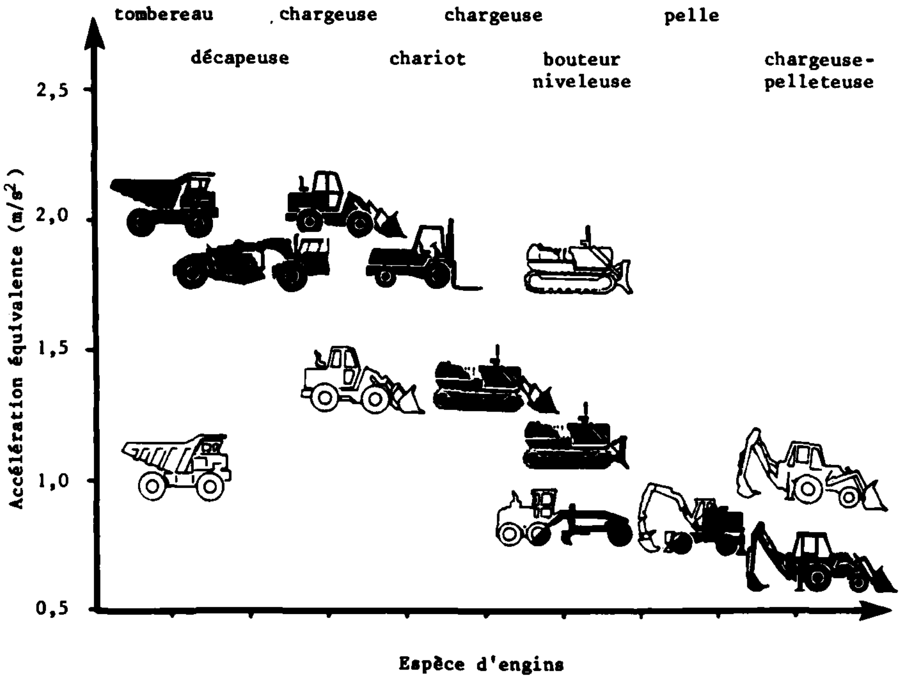

Figure 1 : Comparaison des accélérations équivalentes moyennes relevées au poste de conduite des divers engins étudiés par :

○ Lundström et Lindberg

● l'I.N.R.S.

◑ résultats identiques.

(b) Direction d'exposition privilégiée au niveau de l'assise du siège. D'une façon générale, les accélérations efficaces pondérées en intensité et en fréquence sont du même ordre de grandeur suivant les axes X et Z (cf. figure 2a et b). On note cependant, une prédominance de l'axe Z pour les véhicules montés sur pneumatiques effectuant principalement du roulement et de l'axe X dans le cas des pelles, chargeuses-pelleteuses, bouteurs et chargeuses sur chenilles en phase de creusement, reprise au tas ou décaissement.

Ces remarques quant à la prédominance d'une direction par rapport à une autre, ne sont valables que pour les vibrations relevées au niveau de l'assise du siège. Au niveau du plancher, les caractéristiques vibratoires sont différentes car, d'une part, on supprime l'effet du siège et d'autre part, la position du point de mesure par rapport aux centres de tangage, de roulis et de lacet est différente. Les intensités des accélérations efficaces pondérées relevées suivant les axes X et Y sont, dans l'ensemble, significativement corrélées à celles relevées suivant l'axe vertical ($p < 0,05$). Cette constatation n'est pas vraie quand l'axe X est comparé à l'axe Z dans le cas des engins montés sur chenilles qui sont amenés à effectuer des tâches de poussage, ripage, reprise au tas, pour lesquelles les efforts s'opèrent longitudinalement.

2.2. Efficacité des sièges pour atténuer les vibrations transmises au conducteur

La plupart des engins étudiés étaient équipés d'un siège muni d'un système antivibratile selon l'axe vertical Z (suspension mécanique souple et/ou dans certains cas, garnissage de la sellerie). Par contre, aucun des sièges testés n'était doté d'une suspension avant-arrière. La figure 3 récapitule les valeurs du rapport de transmission R_z obtenues entre l'assise du siège et le plancher.

P : pelles
N : niveleuses
B : bouteurs

Ch_c : chargeuses/chenilles
CP : chargeuses-pelleteuses
Ch_p : chargeuses/pneus

C : chariots
T : tombereaux
D : décapeuses

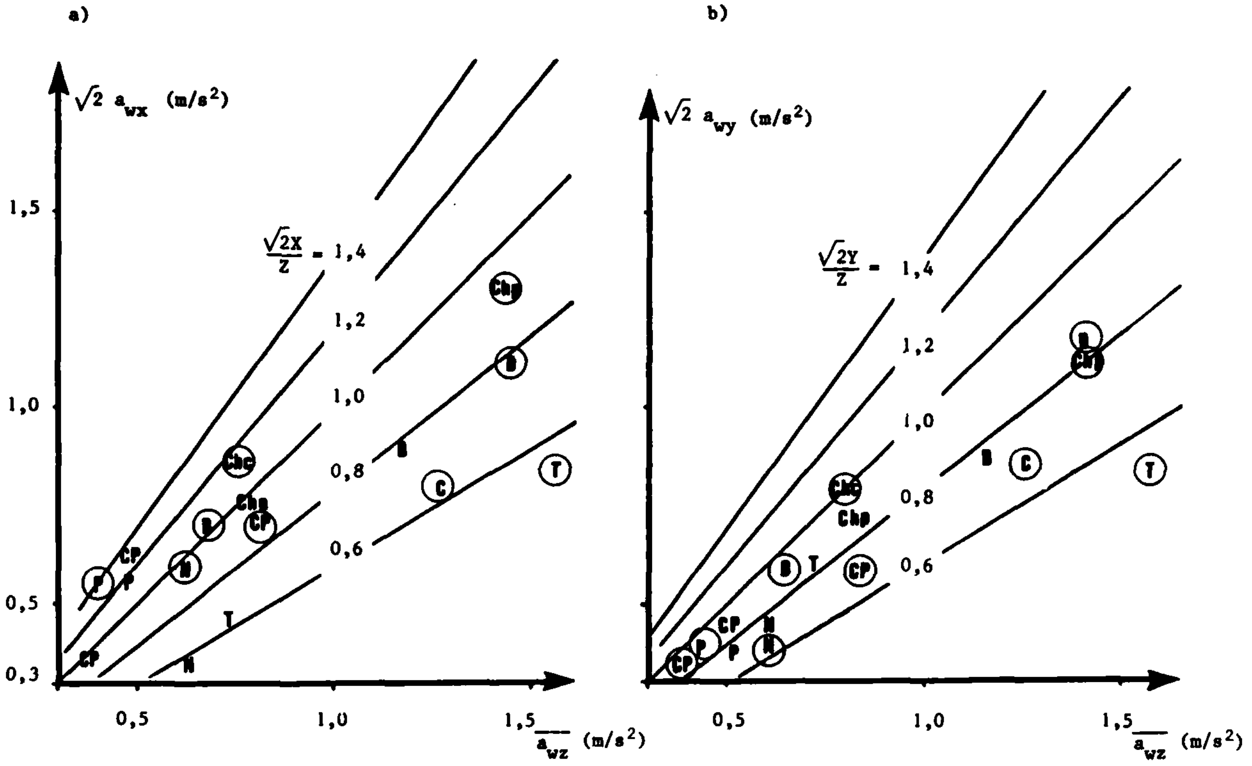

Figure 2 : Comparaison des valeurs moyennes des accélérations efficaces pondérées en fréquence et en intensité relevées suivant l'axe avant-arrière ⌊a)⌋ ou latéral ⌊b)⌋ par rapport à l'axe vertical. Comparaison entre les résultats moyens de Lundström et Lindberg (P) et de l'I.N.R.S. (Ⓟ).

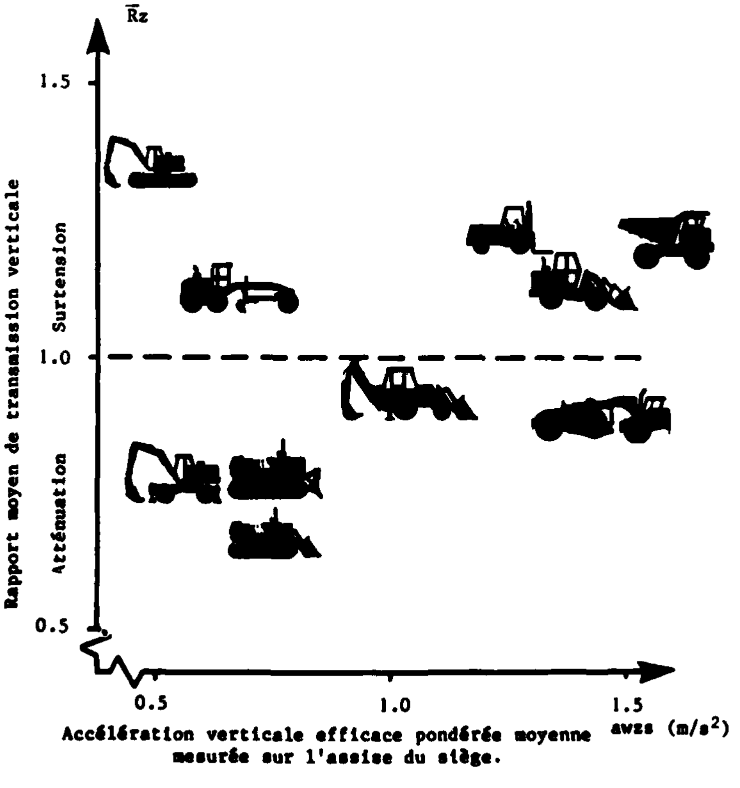

Figure 3 :

Valeurs moyennes prises par le rapport de transmission verticale (R_z) en fonction de l'espèce des engins.

On notera que :

- Ce sont les engins montés sur pneumatiques qui présentent le plus de problèmes étant donné les valeurs élevées de l'accélération équivalente. En effet, les sièges de plus de 80 % des véhicules de ce type faisaient de la surtension. Cette observation s'explique aisément par des considérations relatives à la distribution de l'énergie vibratoire en fonction de la fréquence. En effet, les engins montés sur pneumatiques ont un spectre vibratoire riche en basse fréquence de 1 à 3 Hz. Pour atténuer de telles vibrations, il faut une suspension relativement sophistiquée à grand débattement, ce qui n'est pas toujours possible vu les contraintes de place et les exigences de conduite.
- Les engins montés sur chenilles sont généralement équipés de sièges qui atténuent globalement l'intensité vibratoire selon l'axe Z. Ces engins ont un spectre vibratoire uniformément réparti entre 1,5 et 10 Hz. Or, la plupart des suspensions que l'on trouve dans le commerce, atténuent les vibrations à partir de 2,5 - 3 Hz. C'est pourquoi les valeurs de R_z obtenues pour ce type de véhicule sont inférieures à l'unité. Cependant, même pour ces engins, les vibrations en dessous de 3 Hz sont amplifiées, le rapport R_z ne traduisant qu'une moyenne globale sur toute la plage fréquentielle 1 - 80 Hz.
- Les sièges des engins les moins vibrants selon l'axe vertical (pelles et niveleuses) ont tendance à faire de la surtension. Cette observation s'explique par la non linéarité des caractéristiques des sièges aux faibles niveaux. Elle souligne la nécessité de maîtriser les frottements de la cinématique et le vieillissement du siège.

La figure 4 donne les valeurs de R_z obtenues pour chaque essai avec les chargeuses sur pneus, les chargeuses-pelleteuses et les chariots. Il est clair pour ces engins que les plus hauts niveaux d'a_{wz} observés sur l'assise, sont significativement liés au dysfonctionnement du système antivibratile du siège selon l'axe Z ($r = 0,70$, $p < 0,001$). Il suffirait donc d'équiper ces engins avec un siège muni d'une suspension efficace pour réduire l'intensité vibratoire d'au moins 50 %.

L'application des prescriptions des normes de code d'essai de sièges NF E 90-451 et E 58-074 pourrait très probablement remédier à cet état de fait.

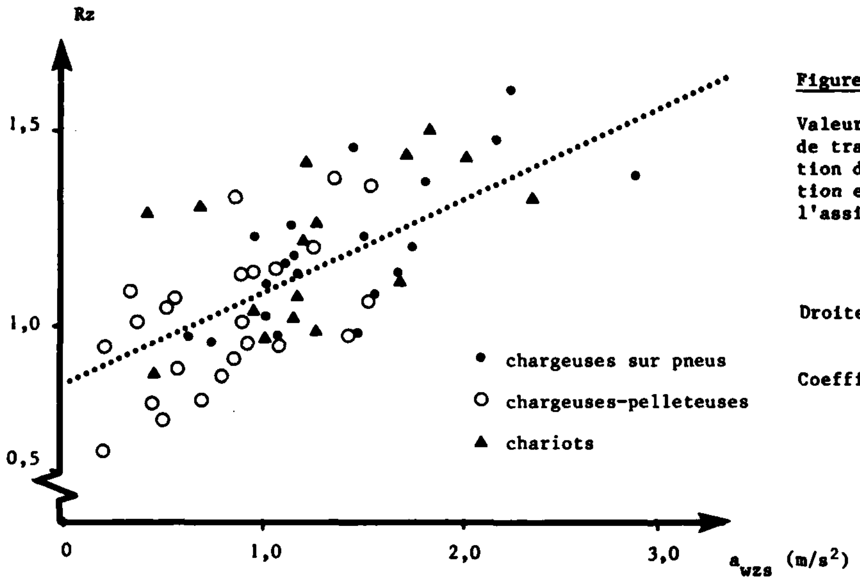

Figure 4 :

Valeurs individuelles du rapport de transmission verticale en fonction de l'intensité de l'accélération efficace pondérée relevée sur l'assise du siège.

Droite de régression :
$R_z = 0,85 + 0,23\ a_{wzs}$

Coefficient de corrélation :
$r = 0,70$; $p < 0,001$

2.3. Courbes enveloppes spectrales des accélérations relevées à la base des sièges.

A titre d'exemple, nous avons donné dans la figure 5, les courbes enveloppes maximale, moyenne et minimale des D.S.P. des accélérations X, Y et Z relevées en pied de siège sur les chargeuses équipées de pneumatiques (toutes tâches confondues). Dans l'ensemble, on constate que la forme des courbes de D.S.P. est en moyenne peu affectée par la tâche, si l'on excepte les chargeuses sur pneus et surtout les chargeuses-pelleteuses. Cette forme, pour une espèce donnée d'engins, est relativement bien typée, surtout selon l'axe vertical. C'est ainsi que par exemple, on observe pour cet axe, un pic d'énergie prédominant dans les bandes fréquentielles suivantes :

- 1,5 - 2 Hz : tombereaux, camions tous chemins et décapeuses non suspendues,
- 1 - 2,5 Hz : chargeuses sur pneus (roulement),
- 2 - 3 Hz : chariots de chantier et niveleuses,
- 1 - 4 Hz : décapeuses suspendues.

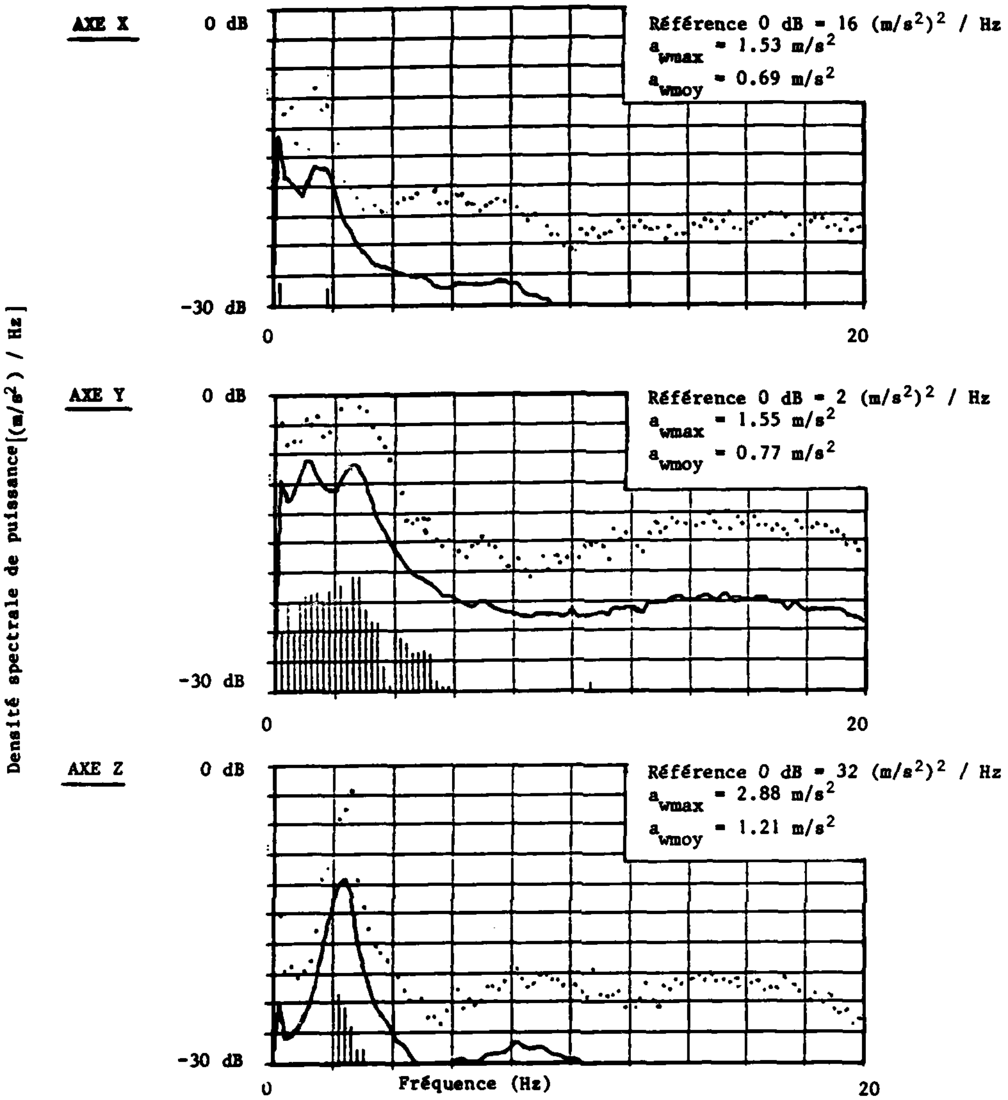

Figure 5 : Courbes enveloppes maximales (.....), moyenne (———), minimale (|||||) des D.S.P. des accélérations X, Y et Z, relevées sur les chargeuses sur pneus, toutes tâches confondues. aw_{max} et aw_{moy} sont les accélérations efficaces pondérées correspondantes.

3. DISCUSSION

3.1. *Comparaison des résultats obtenus avec ceux de Lundström et Lindberg* [13].

Les résultats de l'I.N.R.S. ont été comparés à ceux obtenus par Lundström et Lindberg qui ont évalué la contrainte vibratoire au poste de conduite de 56 engins pour la plupart différents de ceux que l'on a mesurés. Leurs évaluations ont été réalisées au cours d'un ou de plusieurs cycles de travail complets de 15 à 25 minutes.

Ils ont obtenu dans le cas des tombereaux des valeurs d'accélération équivalentes, au niveau du siège, plus faibles en moyenne que celles de l'I.N.R.S. (1 m/s^2 environ au lieu de 2 m/s^2). Cette différence s'explique par le fait que leurs mesures incluaient pour ce type d'engin, en plus d'une phase de roulement sur piste et sur route asphaltée, une phase de chargement. Il en est de même pour les chargeuses sur pneumatiques ; les valeurs d'accélération équivalente étaient de 1,3 m/s^2 en moyenne selon l'étude suédoise au lieu de 1,9 m/s^2 (reprise au tas) et de 2,3 m/s^2 (roulement) pour l'étude I.N.R.S. Par contre, nous avons trouvé des valeurs analogues pour les chargeuses sur chenilles (1,2 et 1,4 m/s^2), les pelles et les chargeuses-pelleteuses en phase de creusement et les niveleuses (0,9 m/s^2). Enfin, Lundström et Lindberg donnent des intensités plus fortes pour les bouteurs (1,8 m/s^2 en moyenne au lieu de 1,2 m/s^2) qui s'expliquent par les conditions opératoires qu'ils ont rencontrés (sol gelé).

Les différences observées nous amènent à rappeler que l'on a recherché volontairement, dans un objectif *premier de code d'essai de siège*, un "majorant" de la contrainte vibratoire dans des conditions d'utilisation typique correspondant à une journée de travail. Dans la réalité, il est sûr que les opérateurs ne sont pas exposés de manière continue à de telles intensités, 8 heures par jour. C'est ainsi que les conducteurs de tombereaux et camions tous chemins sont astreints à des périodes de fortes expositions lorsqu'ils conduisent sur des pistes de chantier mal entretenues et à des périodes de moindre exposition au cours du chargement de leur véhicule. Une estimation correcte de l'intensité moyenne transmise au conducteur au cours d'une journée de travail aurait donc nécessité la définition préalable de tâches typiques (comme il l'a été fait par Lundström et Lindberg), la connaissance de la répartition de ces tâches au cours de la journée et la prise d'un très grand nombre d'échantillons de mesure. Cela était en dehors de notre objectif. C'est pourquoi nous avons cherché seulement à faire des comparaisons d'un engins à l'autre de façon à connaître les plus vibrants.

3.2. Pertinence des classes spectrales des vibrations d'excitation retenues pour les essais de sièges en laboratoire (norme E 58-074).

Les résultats présentés dans le paragraphe 2.2 relatifs à l'efficacité des sièges pour atténuer les vibrations montrent que, bien souvent, la suspension verticale du siège n'est pas adaptée au véhicule sur lequel il est monté. Il y a donc nécessité d'appliquer les codes d'essais de sièges définis par les normes françaises NF E 90-451 et E 58-074. Ces normes préconisent, afin d'obtenir la plus grande fidélité des résultats, d'effectuer les essais sur un simulateur de vibration. La représentativité des essais dépend donc avant tout du choix des processus d'excitation. La norme E 58-074, spécifique aux engins de terrassement, définit 4 classes spectrales de vibration d'entrée verticale en fonction de l'espèce des engins (cf. figure 6). Il s'agit de processus aléatoires, à distribution d'amplitude gaussienne, définis par leur densité spectrale de puissance et leur valeur efficace.

Nous avons tenté de vérifier la pertinence des classes spectrales pour les engins qu'elles sont supposées représenter en les comparant aux courbes enveloppes de D.S.P. des accélérations relevées à la base du siège, présentées dans le paragraphe 2.3. et d'en étendre l'application (s'il y a nécessité d'en élaborer de nouvelles) aux engins de chantier non inclus jusqu'à présent dans la norme E 58-074 (tombereaux et camions de chantier et pelles hydrauliques sur pneumatiques et sur chenilles). D'autre part, pour certains engins (chariots de chantier, tombereaux, camions tous chemins et bouteurs), les vibrations horizontales sont importantes, voire prédominantes (pelles et chargeuses-pelleteuses). Il y aurait donc lieu d'envisager d'équiper les sièges avec une suspension avant-arrière ou latérale, d'où la nécessité d'élaborer pour ces véhicules des classes de vibrations d'entrée horizontales.

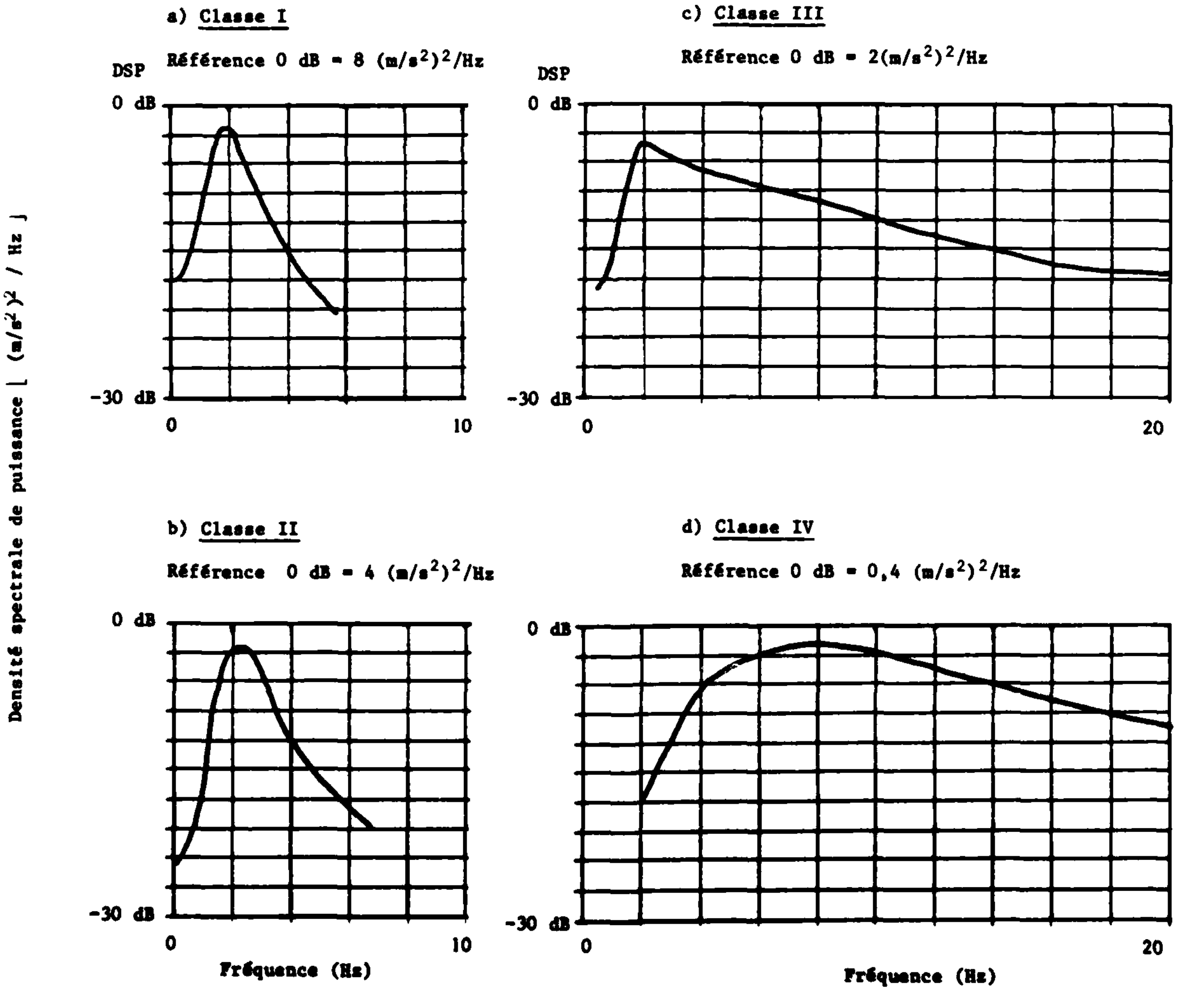

Figure 6 : Graphes des 4 classes spectrales de vibration d'entrée, préconisées par la norme E 58-074 pour les codes d'essai de sièges d'engin de chantier selon l'axe vertical.

On a considéré une classe spectrale comme pertinente pour une espèce spécifique d'engins, dans la mesure où il y a cohérence avec la répartition fréquentielle des courbes enveloppes obtenues (surtout aux basses fréquences pour le filtrage des sièges) et les valeurs supérieures des accélérations efficaces pondérées <u>mesurées</u> (a_w).

(a) Vibrations verticales :
Les 4 classes définies dans la norme sont quasiment suffisantes pour caractériser en fréquence et en intensité tous les véhicules étudiés. Les différentes espèces d'engins pourraient être classées comme suit :

- Classe I : tombereau et camion tous chemins, décapeuse non suspendue.
- Classe II : décapeuse suspendue, chariot de chantier, chargeuse sur pneumatiques (roulement), chargeuse-pelleteuse (toute tâche sauf creusement).
- Classe III : chargeuse sur pneumatiques (reprise au tas et chargement), chargeuse-pelleteuse (creusement) et niveleuse.
- Classe IV : chargeuse sur chenilles, bouteur sur chenilles, pelle toutes catégories (creusement).

(b) Vibrations horizontales :
Aucune des classes spectrales recommandées par la norme E 58-074 n'est représentative de ce que l'on trouve selon les directions horizontales. Il y aurait donc nécessité d'en établir de nouvelles, à savoir, une classe V (pic d'intensité entre 1 et 2 Hz, $a_w = 0{,}8\ m/s^2$) qui s'appliquerait plus particulièrement aux décapeuses, chariots de chantier, chargeuses sur pneus, chargeuses-pelleteuses et bouteurs et une classe VI (plat entre 1 et 10 Hz, $a_w = 0{,}6\ m/s^2$) qui concernerait les chargeuses sur chenilles et éventuellement les pelleteuses selon l'axe X. Les niveaux relevés sur les niveleuses et les pelleteuses (axe Y) sont suffisamment faibles pour ne pas justifier de suspension.

<u>Remarque</u> :
L'atténuation des vibrations basses fréquences, telles que celles correspondant à la classe V proposée (pic d'intensité vers 1 Hz), nécessiterait une suspension à grande course, ce qui n'est pas souhaitable du fait des contraintes de contrôle des véhicules. En fait, l'intérêt principal d'une suspension horizontale, pour ces véhicules, réside dans la possibilité d'atténuer l'aspect impulsionnel du signal. C'est pourquoi, il nous semble indispensable d'utiliser comme processus d'excitation, un signal non seulement représentatif en fréquence mais aussi en distribution d'amplitude.

4. CONCLUSION

Il ressort donc de l'analyse des signaux accélérométriques enregistrés sur l'assise du siège et sur le plancher, selon les directions verticale, avant-arrière et latérale, que :

(a) Les contraintes vibratoires globales calculées en référence à la norme AFNOR NF E 90-401, pour les véhicules montés sur pneumatiques en phase de roulement (tombereaux et camions tous chemins, décapeuses automotrices, chariots automoteurs, etc.) sont généralement plus sévères que celles trouvées pour les pelles hydrauliques et chargeuses-pelleteuses, lors du creusement de tranchée au point fixe. En ce qui concerne ces derniers engins, il se peut que la méthode préconisée sous-estime la contrainte vibratoire réellement subie à la valeur moyenne de l'intensité vibratoire qui est, dans ce cas, fortement fluctuante en fonction de l'opération effectuée dans le cycle de travail. S'il se révélait que la sensibilité des individus est fortement influencée par les pics d'intensité, ce type d'engins apparaîtrait certainement comme plus nuisible.
En moyenne, la direction privilégiée, pour les véhicules montés sur pneumatiques en phase de roulement, est l'axe vertical. Dans l'ensemble, les prescriptions de la norme française NF E 58-050, relatives à l'intensité vibratoire maximale transmise aux conducteurs, ne sont pas respectées.
Dans le cas des pelles, chargeuses-pelleteuses, bouteurs et chargeuses sur chenilles, il y aurait prédominance de la sévérité vibratoire selon l'axe avant-arrière pour les tâches de creusement, reprise au tas et décaissement.

(b) Les suspensions verticales des sièges équipant les véhicules testés, notamment ceux montés sur pneumatiques, sont souvent inadaptées. Dans certains cas, il suffirait simplement d'équiper ces engins avec un siège qui ne surtensionne pas aux fréquences du véhicule, pour réduire l'accélélration verticale de plus de 50 %. L'application du code d'essai de siège, en référence aux Normes françaises NF E 90-451 et E 90-074 pourrait très probablement remédier à cet état de fait.

(c) Pour chaque famille d'engins, on a élaboré des enveloppes spectrales représentatives du plus grand nombre d'engins. Dans l'ensemble, elles montrent, pour l'axe vertical, la pertinence des classes spectrales de vibrations existant dans la norme AFNOR E 58-074 relative aux essais de sièges d'engins de terrassement en laboratoire. Cependant, quelques modifications sont suggérées ; en particulier, il est proposé d'inclure les tombereaux et les camions de chantier.
Il y a matière à créer deux nouvelles classes en matière de vibrations horizontales qui pourraient être définies non seulement en fréquence et en intensité, mais aussi en distribution d'amplitude.

Il est envisagé de prolonger cette étude par une campagne d'essai de sièges d'engins de terrassement effectuée conformément à la norme AFNOR E 58-074 modifiée, afin de pouvoir les classer en fonction de leur capacité à réduire les vibrations.

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DISCUSSION

QUANDIEU, FR: I would like to know if the seat characteristics that you described are really non-linear at low intensity?

DONATI, FR: The behavior of the plastic, flexible suspension system, due to friction and the age of the seat, can be non-linear. This explains the very important overloads that we observed with this type of seat.

VAN VLIET, CA: I think the power spectral density (PSD) approach is good for classifying vibration signals. However, taking into account the non-linear characteristics of the passive seat, there are limitations to this approach. For instance, it does not allow you to reconstruct time histories. At present, in Canada, we use reconstructive time histories to evaluate seats because there is no phase information in the PSDs.

DONATI, CA: I agree with you, but it is our opinion that this represents the simplest method for obtaining results, as a first step. It must be pointed out that this method is presently used for acceptance testing of all farm tractor seats in Europe. However, I believe that we should include other factors, such as vibration, in our assessment. We used this method simply for its convenience.

BACK PAIN AND DISCOMFORT RESULTING FROM EXPOSURE TO VIBRATION IN TRACKED ARMOURED VEHICLES

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INTRODUCTION

That the ride of military vehicles can have pathalogical effects on the occupants has been recognized since charioteers rode with their knees bent to attenuate the shocks from the floor of their vehicles. More recently "tank back" was reported by medical officers during and immediately after the 1939-45 war, and similar effects ("jeep back") were noted for trucks and cars (Ref 1). Despite many references to the chronic effects of vibration and shock on humans, there are few data which relate the effects of exposure to the ride characteristics of the vehicle. This is reflected in the second draft of what are probably the most widely used guidelines for human exposure to vibration, ISO 2631 (Ref 2), which stated that "in view of the complex factors determining the human response to vibration, and in view of the paucity of quantitative data concerning man's perception of vibration and his reactions to it....(the guidelines have been prepared)...to give provisional guidance as to acceptable human exposure to vibration". The exposure limits of ISO 2631 are based on "approximately half the level considered to be the threshold of pain .... for healthy male subjects restrained to a vibrating seat".

From the earliest drafts, the standard also expressed the hope that it would lead to the "reporting and critical evaluation of new findings about the effects of vibration on man". That aim has been a consideration during the various surveys of vibration levels in military vehicles which have been undertaken at DCIEM during the past fifteen years. Thus when the Institute was asked by the Base Surgeon at Canadian Forces Base (CFB) Gagetown to investigate several instances of lower back trauma in tracked armoured-vehicle drivers, the opportunity was taken to study the interrelationship of vehicle ride, operator exposure and back pain (Ref 3).

The problem was evident in a pool of drivers attached to the Combat Arms School (CAS), who were required as part of the school curriculum to drive long hours in M113 armoured personnel carriers during training exercises. The Base Surgeon had noted that, within six months, two drivers from the CAS pool ("Pool drivers") had required surgery for lumbar disc herniation. Both men were under age 34, and subsequent investigation revealed that, among 28 CAS M113 drivers with possible back problems, ten had recurrent lower back pain to the extent that time was missed from work. Of the ten, one required surgery during the period of the investigation, and another six, who were free from congenital abnormalities of the spine, were found by X-ray examination to have changes such as degenerative disc disease.

INVESTIGATION OF THE PROBLEM

The actions of the Base Surgeon had, naturally, aroused the awareness of the Pool drivers to the risks associated with the ride characteristics of their vehicles. A three-aspects approach was therefore taken to the investigation. The first aspect was to review the medical history of the Pool drivers for the three years prior to the investigation, and to compare them with those of two other groups of drivers. One group, ("RCR drivers"), drove the same vehicle but for fewer average hours per week. The other group ("Centurion drivers"), drove a slower, heavier vehicle for a similar number of hours per week.

The three groups were roughly similar in size, (18 Pool, 24 RCR, 20 Centurion), and were matched for ages, heights and weights. The age distribution of the RCR drivers was, in fact, slightly skewed toward the left, implying a slightly younger population, but the three groups were not statistically different.

The second aspect of the study was to review the exposure history of the three groups of drivers. This was done using a modified version of the questionnaire developed by Fitzgerald and Crotty (Ref 4). The questionnaire was modified to cover aspects of the driving environment, including types of terrain, speed over different terrain and hours driving per day and per week.

The possible effect of poor posture as a contributory factor to back pain was of concern. However, equipment and techniques necessary to record the posture adopted by the driver in the confined space of an AFV were not available. Therefore, posture was investigated subjectively through questions related to the comfort of the seat, and the need for improvements to the seats of the two vehicles.

The third aspect of the study involved the recording and analysis of the ride characteristics of the M113 and the Centurion. Accelerations were measured in three orthogonal axes at the driver's buttocks, as each vehicle was driven at representative speeds over various types of road and terrain. A one-third octave-band analysis of the data was then compared with the Exposure Limit (EL), the Fatigue Decreased Proficiency Boundary (FDP), and the Reduced Comfort Boundary (RC) of ISO 2631.

Also used was a criterion for assessing human tolerance to high crest-factor acceleration (shock), taking into account the compressive load limitations of the spine. Payne (Ref 5) proposed a single degree-of-freedom lumped-parameter model to approximate the gross mechanical characteristics of the human spine. The model consists of a simple linear mass-spring system with damping that is proportional to velocity. As the system is excited by an acceleration-time history, it gives as an output a corresponding time history of the compressive deflection of the spring. A Dynamic Response Index (DRI), representing the peak value of the compressive deflection, is determined for each peak in the acceleration-time history.

Allen (Ref 6) has proposed a specification for human tolerance to repeated shocks, based on the DRI model and on the concept that structural fatigue or damage is cumulatively linear to the point of rupture (Miner's Rule). The implementation of the proposal provides a means of quantifying tentatively the occurrence and severity of shocks in an acceleration-time history, and is used by the Institute as an interim method for assessing cross-country vehicle ride quality.

In the proposal, Allen has specified exposure limits representing various degrees of discomfort as a function of the number of repeated shocks: Passenger Comfort (PC), Moderate Discomfort (MD), and Severe Discomfort (SD) (see Figure 1). In addition, a five per-cent back-injury criterion is specified, based on vertebrae breaking strength data from which the parameters of the DRI spinal-loading model were defined (DRI = 20 g corresponds to 50 per-cent probability of spinal injury (Ref 7)), and on the correlation of DRI to aircraft-ejection injury rates (Ref 8).

The DRI model and Allen's proposal for human tolerance to repeated vibration shocks were implemented at the Institute on an analogue and a digital computer, and used to analyze samples of the M113 and Centurion off-road (cross-country) Z-axis acceleration-time histories.

RESULTS

Medical Records

Chi squared analysis of the records showed that the three groups of drivers had not differed in their frequency of visits to the Medical Investigation Room (MIR) in the three years prior to the study. However, the Pool drivers reported significantly* more back pain complaints than the RCR drivers, or than the RCR and Centurion driver groups combined. Similarly the Pool drivers mentioned their vehicle as a causative factor in their complaints significantly more often than the other two driver groups.

Questionnaire Results

It was to be expected that the MIR records would not represent the total incidence of back pain in any of the driver groups. It appeared probable that some back pain was considered too minor to warrant a visit to the MIR, and was self-treated with massage, rest etc. The data from the questionnaire supported that assumption, indicating that more men in all three driver groups suffered from back pain than was shown by the MIR records. Eighty-nine per cent of Pool drivers, 46 per cent of RCR drivers, and 55 per cent of Centurion drivers reported suffering from backache or back pain.

Median Chi square tests showed no significant difference in the proportion of sufferers in each group having a prior accident involving the back. From that observation it is argued that prior injury involving the back is not the major causative factor of the higher incidence of back problems in the Pool group.

The questionnaire responses indicated that there were differences in the sports activities of the three groups. Significantly more RCR drivers participated in jogging and swimming than the other drivers; significantly more Centurion drivers played golf than drivers in the other two groups.

Median Chi square tests showed no significant difference between the driver groups in terms of prior experience driving their vehicles. Examination of the distribution of the questionnaire responses showed, however, that there was a trend to the RCR and Centurion drivers having had fewer years of armoured fighting vehicle (AFV) driving experience than did the Pool drivers. This agreed with expectations from the career progression pattern, since AFV drivers tended to be streamed into the CAS on the basis of experience. Pool drivers were found to be spread over all levels of experience, whereas the RCR drivers were skewed towards less experience, and the Centurion drivers more markedly so. Therefore, the type of driving and the cumulative effect of experience may be confounded.

The questionnaire results confirmed the selection of the two comparison groups. The amount of driving per week was found to be the same for Pool and Centurion drivers, with the RCR group driving significantly less. The number of hours per week driven across country was also the same for the Pool and Centurion drivers, and significantly less for the RCR drivers (see Table I), and the Pool and Centurion drivers drove significantly fewer hours per week on gravel roads

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* Throughout the analysis significance is at the .05 level or better.

than did the RCR drivers.

TABLE I

NUMBER OF HOURS PER WEEK DRIVING CROSS COUNTRY

	Groups		
	Pool Drivers	RCR Drivers	Centurion Drivers
Less Than 10 Hours	2	13	1
Between 10 and 30 Hours	8	3	6
Between 30 and 50 Hours	6	0	9
Greater Than 50 Hours	2	0	2
No Reply	0	8	2

Factor Analysis

From the analysis of the MIR records and the questionnaire data, several differences were noted between the Pool drivers and the two other groups, any of which could have been a contributory cause of the higher incidence of back pain experienced by the Pool drivers. The following differences were considered for further analysis:-

i. driver age
ii. driver physique (weight/height ratio)
iii. years of driving experience
iv. hours driven per week
v. total hours/week on all terrain-(road, gravel, cross-country)
vi. driving speed over terrain (roads, gravel, cross-country)
vii. mass of the vehicle

These variables, plus the presence or absence of back pain were subjected to factor analysis. Four factors were used, and a minimum loading of 0.3 was required on each factor. Variables included in the same factors as presence of back pain were considered to be the major contributors to that condition. Two factors were found to include back pain. The variables associated with back pain were high total hours driven per week, long hours on all three types of terrain, and a high personal weight to height ratio.

Variables which grouped together in a third factor were no back pain, heavy vehicle weight, slow driving speeds and long hours cross-country. Those factors were interpreted as representing the Centurion drivers' environment. Other variables which grouped together were older drivers, more AVF driving experience and slow driving speeds across country. No significance was attached to this factor, but it could be interpreted as indicating either that older drivers learn to drive more slowly, or that they are less tolerant of shock than younger drivers.

Ride Data

The acceleration levels measured on the driver's seat in the two vehicles indicated that Z-axis levels in the M113 were considerably higher for off-road conditions than for paved- or gravel-road conditions. In the much slower and heavier Centurion, Z-axis levels did not differ significantly between road and cross-country conditions, and were less intense than those in the M113 (Ref 9).

For cross-country conditions in the M113 (20 kph) and in the Centurion tank (12 kph), the Z-axis FDP boundary was exceeded in the vehicles (at the driver's seat) after one hour and eight hours respectively, and the EL boundary after four hours and 24 hours respectively (Table II) (Ref 9). In the M113 ride sample, crest factors as high as 13 were encountered. When the crest factors exceed six, the effects of the motion upon health, fatigue and comfort may be underestimated by the ISO 2631 criteria (Ref 2). In the Centurion Tank, crest factors were less than six.

TABLE II

M113 AND CENTURION TANK CROSS-COUNTRY Z-AXIS VIBRATION EXPOSURE LIMITS, AT THE DRIVER'S SEAT, USING ISO 2631 AND ALLEN'S DRI-TOLERANCE CRITERIA

	Acceleration	ISO 2631			DRI/ALLEN		
Vehicle/Speed	Crest Factor	RC	FDP	EL	PC	MD	SD
M113 APC 20 kph	13	<1 min	1hr	4hr	4 min	4hr	—
Centurion Tank 12 kph	—	1hr	8hr	24hr	—	—	—

The results of the DRI-Allen computer analysis are summarized in Table II, and indicate that the PC and MD boundaries would be exceeded in the M113 after four minutes and four hours respectively. During the 3-minute sample, 12 shocks exceeding 1 Gz were observed, producing values of DRI ranging from 1.01 to 2.79, with a mean value of 1.65 and a standard deviation of

0.56 (Ref 10).

Note that the effect of gravity-bias acceleration was suppressed at the output of the analogue computer (DRI model) in accordance with standard practice (Ref 11), and that the digital-computer program did not accumulate DRI values (DRI< 1.0) for accelerations less than 1 Gz. It is not until the spinal compressive-spring force completely counteracts the weight-force vector that the vertebral column becomes the primary weight-bearing element. Hence, accelerations less than 1 Gz are not significant in the spinal-loading model.

No values of DRI were generated for the Centurion Tank. This is because the tank cross-country data did not contain acceleration shocks exceeding 1 Gz.

DISCUSSION

The major limitation to the study was the small sample size and their limited distribution across the variables. The sample size, however, was dictated by the number of Pool drivers. The effect of such a small sample on the statistical analysis is an obvious weakness. Therefore, the results of the study must be considered as indications of trend, rather than robust cause-effect relationships.

Other reservations must be expressed about some of the data. Upon identifying back trauma among the Pool drivers, the Base Surgeon had instituted a limitation in driving hours, so that it was not possible to validate the questionnaire returns for the hours driven in different terrain. Some members of the Pool and Centurion groups indicated that they were driving between 50 and 70 hours a week. It is questionable whether those AFVs would be continually driven for more than ten hours a day on a routine basis, and it is possible that the total hours include time at rest, or in a hide. It has been noted during other exercises that the drivers of such vehicles take any opportunity to move them, so that, although they are nominally "at rest", they are actually often moving about the "rest" area. When at rest the vehicle engines are left running. The drivers would therefore be exposed to the vibration from that source, if not from actually driving. Overall, then, the details of the vibration stress on drivers reporting long hours per week are not clear. Since the time exposure limits of ISO 2631 are logarithmically related to acceleration, however, they become increasingly imprecise for exposures greater than four hours, and the questionnaire data were therefore judged to be adequate for the study.

Another concern is whether the incidence of back pain reported by the Pool drivers differs significantly from that reported in the general population of drivers or people with vibration-induced injury. The use of two comparison groups did not, in itself, guarantee that the Pool drivers would be compared to a "normal" population. Unfortunately, no data have been found which indicate the "normal" incidence of back pain in the Canadian Forces. The data from the three groups were therefore compared with data from the British Army (Ref 12) and with Canadian farmers (Ref 13), tractor drivers (Ref 14) and interstate bus drivers (Ref 15). Based on the findings of those studies, it appeared that the control groups did have a higher incidence of back pain than "normal". If this is the case, then the comparisons between the groups may underestimate the effects of common factors such as age, driving experience and driving posture.

The relationship of driving posture and vehicle-ride effects on back trauma is of major interest to this symposium. Although posture was recognized as an important factor in the consideration of causes of back pain, and although questions on the design of the seat were included in the survey, it was not possible to treat posture systematically. Some M113 drivers indicated in their questionnaire responses that they used their back rests. It was found, however, that it was not possible to drive either the M113 or the Centurion with the back in contact with the back rest without adopting a very uncomfortable posture. Lap belts were provided in the M113, but if used they held the driver's buttocks in place, forcing him to lean forward to reach the controls. The relative position of the driver's hatch and the seat in both vehicles also made it difficult to sit upright. The resulting forward hunched posture almost certainly resulted in flattening of the lumbar lordosis and compression of the lumbar discs at their forward edge, which would exacerbate any stress on the spinal column.

Given the findings of Fitzgerald (Ref 16) that proper restraints, back support and torso-thigh angle were of importance to the reduction of the incidence of back pain among aviators, it seemed reasonable to conclude that the poor posture of both the M113 and the Centurion seats contributed to the drivers' complaints. If poor posture was the only factor contributing to the incidence of back pain, however, then no difference would be expected between the two M113 driver groups. That was not the case; whereas 80 per-cent of RCR drivers and 88 per-cent of Pool drivers reported the M113 seat very uncomfortable, only 42 per-cent of RCR drivers reported back pain, compared with 89 per-cent of Pool drivers. That poor posture does induce back pain was evident by the responses of the Centurion drivers, 55 per-cent of whom suffered from back pain.

As noted from the factor analysis, the ride characteristics of the two vehicles do imply that there would be differences in the frequency of back pain. The results of the ride analysis based on ISO 2631 indicate that the Exposure Limit is not exceeded in the Centurion in any speed/terrain condition, whereas that limit is exceeded after four hours in the M113 when travelling cross-country at speeds of more than 20 kph. Given the differences in hours driven cross-country, this could explain the differences in reports of back pain between the Pool and RCR drivers.

As noted at the outset, one of the prime aims of the study was the reporting and critical evaluation of new findings about the effects of vibration on man. That high levels of vibration, coupled with long hours of exposure result in a high incidence of back pain cannot be called a new finding. The fact that the exposure levels predicted by ISO 2631 do appear to have some relationship to the observed incidence of back pain is of interest. While a significant amount of effort has been put into validating the Reduced Comfort and the Fatigue Decreased Proficiency limits of the standard, there have been few studies of the Exposure Limits, which are, in fact, often the most critical aspects of military operations.

The validation of Allen's proposal for human tolerance to repeated shocks is not the purpose of this paper. The assumptions made by Allen are that (1) discomfort is caused by the dynamic compression peak loads in the spinal column, (2) these loads can be quantified by the DRI, and (3) damage is a linear function of accumulated loads. The first assumption is disputable in that discomfort is subjective and often due to non-specific stress; the second because spinal-column stiffness is not independent of load level. Data are required to determine whether the variable stiffness of the spinal column causes significant discrepancies in subjective responses to a given DRI value. The third assumption also requires validation, or a demonstration of non-linear effects.

A question also exists concerning the significance of input accelerations that generate values of DRI less than 1 g in evaluating ride quality (17). Although such values were not used in the cumulative PC and MD limits shown in Table II, their effects upon soft-body tissue may be an important factor in ride-discomfort analysis.

Although it is tempting to compare the four-hour Exposure Limit predicted by ISO 2631 with the four-hour Moderate Discomfort limit predicted by DRI-Allen, such comparisons are not justified. Allen (Ref 6) has cautioned against such comparisons, first because of the preliminary nature of the repeated-shock proposal, and secondly because of uncertainties regarding the time-dependency assumptions in ISO 2631. For the purpose of this study, suffice it to say that the cross-country ride qualities of the M113 are shown to be significantly more severe than those of the Centurion when evaluated by either ISO 2631 or Allen's proposal for human tolerance to repeated shock using the DRI spinal model.

On the basis of the evidence it seems not unreasonable to conclude that the high incidence of back pain observed in the Pool driver group was the result of poor posture and exposure to intense levels of vibration and shock for periods exceeding the exposure limits recommended by ISO 2631, and that the incidence of back pain among RCR and Centurion drivers was related to poor driving posture.

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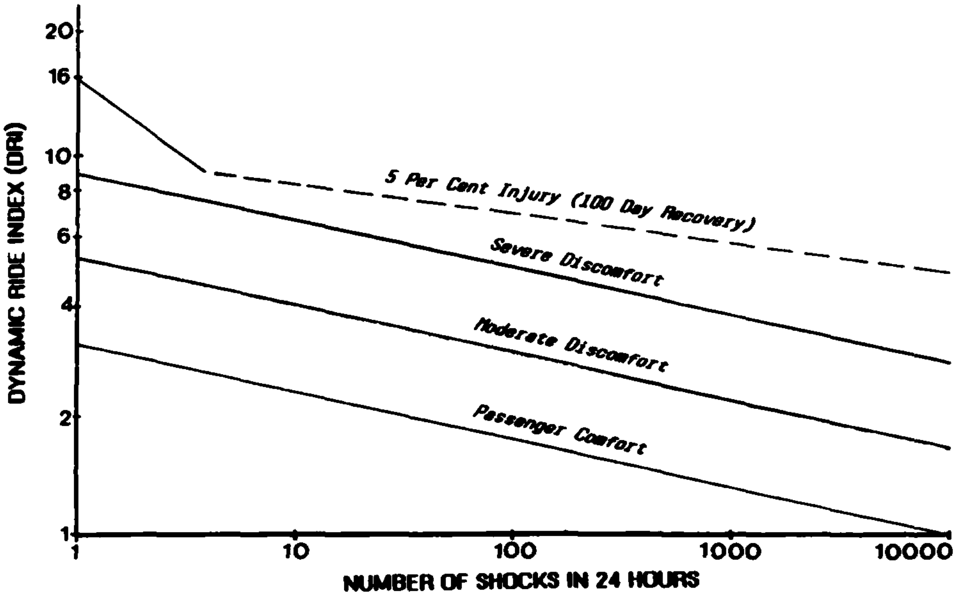

FIGURE 1. Suggested exposure limits representing various degrees of discomfort and a five per cent back-injury criterion, as a function of Dynamic Ride Index (DRI) and number of repeated shocks per day (After Allen (Ref 6)).

DISCUSSION

TROUP, UK: I wonder if you could say a little about the studies of the spine which led to predictions of injury. I think this is rather an interesting and important topic.

BOWDEN (re BEEVIS and FORSHAW paper), CA: I cannot say too much about the paper. Allen's proposal (AGARD Conference Proceedings No. 253, pp. A25-1 to A25-15) was based on a study of aircraft seat ejection injuries. It related the shock of seat ejection to the injuries sustained from that single shock to the pilot when he ejected. He found that the model, which is now used in the Standard in the United States Air Force and is based upon the Dynamic Response Index (DRI), was established on that sort of data. Allen simply extended it, using a principle of relating multiple shocks in a cumulative way, to cover situations in which subjects were exposed to repeated shocks in aircraft or vehicles. That's about all I can say about the paper.

SANDOVER, UK: I can add that Allen also used information from various studies, my own among them, in which people had been subjected to a number of shocks as part of another experiment. There were some comments on the subjective severity, so he used both the original DRI concept and some field data.

LANDOLT, CA: Regarding the graph of the Dynamic Ride Index versus the number of shocks per 24 hours, would you know where the data of Beevis and Forshaw fits into that graph? Would they be near the Passenger Comfort line?

BOWDEN (re BEEVIS and FORSHAW paper), CA: The estimate of duration was based on questionnaire data, and the authors suspected that the actual driving exposure may have been less than indicated because the drivers would report rest periods inside the armoured vehicles, as well as the periods in which they were actually driving cross country. As Beevis and Forshaw noted in their paper, the APC DRI values ranged from 1.01 to 2.79; which, for exposure durations of less that 4 minutes, would lie below the Passenger Comfort Boundary.

PRIVITZER, US: You said that the DRI was based on vertebral body compressive experiments. It is actually directly based on ejection statistics; and, indirectly, related to vertebral body compressive strength, because the ejection statistics were from ejections in which vertebral injuries were sustained. The DRI values that you have reported are so low that I fail to see the significance in mentioning them.

BOWDEN (re BEEVIS and FORSHAW paper), CA: I would say that, in terms of ejection, the values are very low, being less than 3G. However, in this Symposium, we are considering the problem of repeated and cumulative exposures to stresses which are not individually hazardous; and, therefore, I think that the lower levels of stress are of interest. Does that answer your question?

PRIVITZER, US: I may have misinterpreted that one slide, but it looked like the severity of exposures decreases with the number of exposures. It seems that discomfort and severity should increase with cumulative exposures.

BOWDEN (re BEEVIS and FORSHAW paper), CA: The slide is actually a graph from Allen's paper, and it is the DRI index required to produce a given level of discomfort or injury as a function of the number of repetitions of the exposure to shocks of that DRI index. It is an hypothesis. I believe that Allen extrapolated beyond the data for ejection, with a slope somewhat similar to that chosen for ISO 2631; and this is very conjectural.

LOW BACK PAIN AND NARROWED DISC SPACES IN FIGHTER PILOTS

by

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SUMMARY

Compressive forces may play a role in the development of disc degeneration. We measured the disc spaces on latereral x-rays of the lumbar spine in fighter pilots with and without a history of sciatica, and compared them to those of asymptomatic transport pilots. An arbitrary cutoff point for 'normal' was defined and the proportion of each group with narrowed disc spaces determined. Fighter pilots with a history of sciatica had a significantly higher proportion of those with narrowed disc spaces than did asymptomatic transport pilots. Fighter pilots without low back pain had an intermediate proportion with narrowed disc spaces. We conclude that disc degeneration may be accellerated by repeated Gz forces experienced by pilots of fighter aircraft.

abbreviations: LBP = low back pain.

INTRODUCTION

We have recently reported that the prevalence of a history of LBP unassociated with flight was nearly identical in fighter, transport and helicopter pilots(1). Fighter pilots however, had nearly twice the prevalence of chronic pain, pain requiring bed rest and pain radiating to the leg in comparison to transport and helicopter pilots. In the following report the disc spaces measured on lateral x-rays of the lumbar spine were compared in fighter pilots with and without sciatica, and in asymptomatic transport pilots, inorder to determine whether or not fighter pilots are at increased risk for disc degeneration.

Methods

A questionnaire on low back pain on page-reader forms was administered to 373 fighter pilots, 165 transport pilots and 264 helicopter pilots. The pilots in each group were chosen at random from those undergoing annual physical examination and were age matched. Because of the tendency for pilots to play down physical complaints, they were asked to report any history of either low back pain or discomfort, associated or temporally unassociated with flying. Sciatic pain was defined as pain that radiated to the leg. Severity of pain was assessed by whether or not the pain radiated to the leg (sciatica) and/or led to bed rest, or loss of flight time. In addition, pilots were questioned about pain during and immediately after flight. They were assured beforehand that their answers would not effect their flying status. Statistical comparison was done by the chi-square test.

Lateral x-rays of the lumbar spine with the patient in the lateral recumbent position with hips and knees flexed at 45 degrees were evaluated in three groups of pilots; in 64 transport pilots and 58 fighter pilots who denied a history of low back pain, and in 33 fighter pilots who complained of LBP radiating to the leg. All of the pilots were between the ages of 25 and 35 and had flown for at least 6 years. The films were taken at 100 cm-film-focus distance and an 18 cm distance from the mid sagittal plane of the segment to the film. The beam was centered on the body of L3.

The four "corners" of the vertebral bodies were marked in order to quantitatively determine the anterior and posterior disc heights. The distences were measured to the nearest 1 mm. The sacral angle was measured as described previously (2). An arbitrary cutoff point for "normal" was determined and the proportion of each group with narrowed disc spaces was determined for L5-S1, L4-L5 and L3-L4. In addition the anterior border of L3 was measured to assure that the heights of the vertebrae in the three groups were similar. The significance of differences was determined by the chi-squared test and by Fisher's exact test when the numbers were small. A p value of less than 0.05 was considered significant.

*Table 1. The prevalence of a history of low back pain (LBP) unassociated with flight.

type of aircraft	fighter	transport	helicopter
number at risk	373	165	264
LBP (%)			
discomfort	55(14.7)	18(10.9)	26(9.8)
pain	94(25.2)	52(31.5)	70(26.5)
Total	149(39.9)	70(42.4)	96(36.4)

*With permission from Aviation Space Environ Med (in press) V57, 1986

RESULTS

We have shown that the prevalence of low back discomfort or pain unrelated to flight was similar in all three groups of pilots (1)(Table 1). Fighter pilots, however had nearly twice the prevalence of chronic pain and pain radiating to the leg (Table 2). Also even though less pain during flight was experienced by fighter pilots, more of those with pain had discomfort for at least 24 hours after landing (Table 3)

*Table 2. The severity and chronicity of low back pain (LBP) unassociated with flight.

Type of aircraft	fighter	transport	helicopter
Number with LBP	94	52	70
Sciatica	25(25.5**)	5(9.6)	9(12.9)
bedrest	24(25.5**)	7(13.5)	8(11.4)
missed flight	29(30.9**)	7(13.5)	8(11.4)
duration over one year	27(28.7**)	5(9.6)	11(15.7)

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**Significantly more than transport and helicopter pilots ($p < 0.03$)

*Table 3. Low back pain during and immediately after flight.

Type of aircraft	fighter	transport	helicopter
number at risk	373	165	264
Low back			
discomfort	38(10.2)	21(12.7)	61(23.1*)
pain	48(12.9)	8(4.8)	91(34.5*)
Total	86(23.1)	29(17.6)	152(57.6*)
Persistence of pain or discomfort more than 24 hours in those with LBP or discomfort	22(25.6**)	2(6.9)	9(5.9)

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**Significantly more than the other two groups of pilots ($p < 0.04$)

Lateral x-rays revealed that 45.5% of the fighter pilots with sciatica had narrowed disc spaces at L5-S1 measured posteriorly compared to only 3.1% in the control group (Table 4). Fighter pilots with sciatica had nearly twice the frequency of narrowed disc than did fighter pilots without LBP (45.5% versus 25.9%, $p < 0.06$). A trend for an increased proportion of narrowed discs in fighter pilots with sciatica was found for the L4-L5 interspace as well. Anterior measurements showed a similar trend which did not reach statistical significance because of small numbers (Table 5). Sacral angles were not significantly different when comparing the three groups of pilots (Table 6). The anterior border of L3 was similar in all three groups of pilots (37.1 mm in fighter pilots with sciatica, 37.0 mm in fighter pilots without LBP, and 37.8 mm in transport pilots).

Table 4. Posterior disc spaces in pilots with and without low back pain.

	Fighter pilots		transport pilots
	Sciatica	No LBP	No LBP
No at risk	33	58	54
Disc space	No(%)	No(%)	No(%)
L5-S1 1 mm	15(45.5)*	15(25.9)*	2(3.1)
L4-L5 3 mm	11(33.3)*	14(24.1)	6(9.4)
L3-L4 3 mm	1(2.1)	4(6.9)	4(6.3)

*Significantly more than found in transport pilots, $p < 0.004$

Table 5. Anterior disc spaces in pilots with and without LBP

	Fighter pilots		Transport pilots
	Sciatica	No LBP	No LBP
At risk	33	58	64
Disc spaces	No(%)	No(%)	No(%)
L5-S1 10 mm	4(12.1)	7(12.1)	4(6.3)
L4-L5 12 mm	4(12.1)	8(13.8)	3(4.7)
L3-L4 10 mm	4(12.1)	7(12.1)	3(4.7)

DISCUSSION

The main finding in our study is that fighter pilots have an increased prevalence of LBP with radiation to the leg and that this finding is associated with narrower posterior disc spaces in comparisom to transport pilots without LBP. The fact that fighter pilots without LBP also had narrower disc spaces suggests that this phenomonen is related to flight.

Our results should be interpreted with caution. There is considerable intra-individual variation of disc space measurements because of both reader judgement and orientation differences (3). This variation, however is only likely to decrease real differences. In addition different flight profiles may prevent extrapolation of our data to airforce personnel of other countries. Studies therefore in other airforces are warrented to confirm our findings.

Recently Witt et al (4) found no difference in the prevalence of disc degeneration in those with sciatica compared to those without LBP in those over 40 years old and only a small insignificant difference noted in those under 40. Their cohort, however included those between the ages 20 and 70, and degeneration of the disc was not defined. The significant association we observed between sciatica and narrowed disc spaces may have been due to the fact that disc spaces were measured and that our study group was more homogeneous in regards to age, body build and motivation. Other studies, predominently of selected elderly patients have found an increased prevalence of disc degeneration in those with sciatica compared to controls (5-8).

It is not suprising that helicopter pilots have the same prevalence of LBP unassociated with flight as do fighter and transport pilots. Shanahan et al (9) has shown that poor posture is primarily responsible for the back pain experienced by helicopter pilots during flight. Under experimental conditions, with pilots sitting in the usual position with their bodies bent forward and leaning slightly to the left, the same pain was produced under vibrational and non vibrational conditions. Furthermore, the only studies showing an association between vibrational stress and LBP were either uncontrolled or when a control group was available, the vibrational forces could not be separated out from other associated stresses (10,11).

It appears therefore that fighter pilots are a group at increased risk for more severe back problems. Anatomic studies have indicated that disc degeneration begins in early life and is prevalent in young adults (12,13). This process may be aggrevated by the repeated Gs forces experienced by pilots of fighter aircraft. Careful follow-up of such pilots is warrented.

Table 6. Sacral angle in pilots with and without LBP

	Fighter pilots		Transport pilots
	sciatica	No LBP	No LBP
At risk (No)	33	58	64
Degrees	No(%)	No(%)	No(%)
20-29	1(3.2)	6(10.3)	4(6.3)
30-39	10(32.3)	15(25.9)	18(28.1)
40-49	11(35.5)	22(37.9)	26(40.6)
50-59	6(19.4)	12(20.7)	9(14.1)
60+	3(9.7)	3(5.2)	4(6.3)

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RELATIONSHIP BETWEEN BACKACHE AND FLYING DUTY IN JET- AND PROP-PILOTS DEMONSTRATED BY A FLYING WING

by

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SUMMARY

A questionnaire assessment was performed in a collective of 88 jet- and prop-pilots. Approximately half of the pilots suffer from backache. A significant connection between the number of flying hours, annual flying stress and sports activities can not be ascertained. The duration of the sitting posture and G-loads are subjectively classified as being the highest body stress, whereas vibrations play a secondary role. The cold pilot's seat in winter and the uncomfortable harness are objects of particular complaints. Concrete facts indicate that in an effort to avoid vertebral pain the seat must be constructed in such a manner as to avoid excessive posterior pelvis tilt. 50% of the pilots questioned are of the opinion that their flying duty causes health damages.

PROBLEM

Lately the discussion about a connection between military flying duty and possible vertebral damages has increased. So far the interest was predominantly concentrated on the group of helicopter pilots and on the question of premature attrition caused by increased vibrational stress (e.g.2,3,7).

The present study attempts in an informational way to clarify, which importance should be attributed to the problem of "back pain" in jet and prop wings.
Of interest were frequency of back pain, its symptomatology, age distribution, flying stress and clues pointing to possible causes in connection with the flying duty. Moreover, the subjective pilots'assessment of certain workloads during flying duty had to be recorded.

METHODS

The study was conducted as a questionnaire assessment in a collective of 88 pilots and weapon system operators (WSO). It was comprised of 57 jet-pilots resp. WSO, 20 prop-pilots, and 11 pilots flying jet as well as prop aircraft.
47 test persons of the collective were younger than 40 years, 41 subjects were 40 years or older. The questionnaire consisted of 45 single questions, which in turn could be subdivided into a total of 162 variables. In order to improve cooperation and to achieve greater frankness in answering the questions the assessment was performed anonymously.

RESULTS

52.3 %, i.e. approximately half of the collective questioned, states that they suffer from back pain (Fig. 1). In prop-pilots the percentage is somewhat higher than in jet-pilots, but the difference is not significant.
As shown in Fig. 2, the majority of complaints begins gradually and is only present part of the time. While in prop-pilots there is also a certain percentage of prolonged pain, part of the jet-pilots indicate a rather intermittent course. Dragging pain is more often found in prop-pilots, while jet-pilots show a tendency for stabbing pain (Fig. 3). The differences may be attributed to the different operational profile between jet and prop. Both groups state that the complaints have a predominantly dull character.

From the periodic aeromedical examinations we know that in the wing concerned there were only 4 cases in which a root compression could be clinically verified. This corresponds to a frequency of about 3%. Thus, we think that the complaints encountered rather point to alterations in the joints of the vertebral arch and to muscular tensions.

Fig. 4 shows which factors cause unpleasant sensations for the pilots in flight.
For the prop-pilots questioned, the only problems are sitting- respectively working-posture and draught.
In contrast movements of the head under G-loads and the G-load per se have a greater importance for jet-pilots. It is of interest to note that turbulences and vibrations are hardly considered to be straining in both groups. Altogether the individual factors cause an increased amount of unpleasant sensations in the group <u>with</u> back pain.

Every pilot questioned was asked for an assessment within a 5-step graduation how strongly he feels stress by the factors of G-forces, vibration and duration of sitting during flight. The 0-score thereby stands for a complete absence of any subjective strain, whereas a score of 5 corresponds to very high strain.

Here it is of interest to note the high scoring of the duration of sitting in the jet- as well as in the prop-group (Fig. 5). The obvious difference in the assessment of the G-forces is due to the different operational profiles.

It is surprising, however, that prop-pilots classify vibrational stress significantly lower than the jet-pilots. Evidently turbulences encountered in jet aircraft play a greater role than vibrations due to prop-propulsion.

The group having back pain does not significantly differ in its assessment from the group without back pain (Fig. 6). There is, however, a distinct influence of the number of flying hours (Fig. 7). Persons with a high number of flying hours assess G-forces and vibration significantly lower than subjects having a low number of flying hours. This may be a kind of habituational effect. Such habituation, however, can not be identified for the duration of sitting, we rather note a small increase. So this again shows the importance of sitting posture for the pilots independent of their flying experience.

The relatively high amount of uncomfortable sensations in connection with the sitting posture is obviously closely related to the seat construction. Fig. 8 illustrates the essential points of criticism relating to the seat lay-out as stated by the pilots. Especially unpleasant sensations are attributed to the cold seat during winter time, the uncomfortable harness and the absence of upper thigh supports.

It is interesting that the factors "Upper Thigh Support", "Angle of Back Rest Inclination", and "Lower Back Support" are definitely more often criticized by the group experiencing back pain. This points to a certain interrelation. If the layout of these three factors is not appropriate an increased tilt of the pelvis in the sitting posture will result. This in turn causes partial or complete elimination of the lumbar lordosis and induces a higher strain of the dorso-lumbar region (see 5 and 6). The diagram reproduced refers to the ejection seat of a jet aircraft in the flying wing investigated. As for propeller aircraft we were not able to prove a similar interrelationship. That sitting posture independent of specific workload plays a key role with respect to back pain is shown in Fig. 10. Nearly all pilots with back pain also have these complaints when driving a car. Contrary to this, pilots free of pain also normally have no complaints whilst driving.
We were also interested to find out to what extent the frequency of back pain depends on the amount of flying hours.
As shown in Fig. 11 pilots with back pain have significantly higher flying hours than pilots without back pain. The frequency distribution as a function of flying hours is represented in Fig.12.

However, pilots having back pain are also older on the average than pain-free pilots. We suppose that this might essentially be attributed to physiological wear with ageing(Fig. 13). Fig. 14 shows the frequency distribution found in our collective.

Since the number of flying hours also depends on age, we had to find a procedure which would eliminate the influence of age.

To this end we first considered the dependence of flying hours from the view point of age. Every dot in Fig. 15 represents the flying hours of a single pilot in relationship to his age. The regression line indicated illustrates the functional correlation between both parameters. Thus, we were able to predict the average flying hours in our collective relating to each age. The distance of one dot from the straight line is an indication, how much the number of flying hours of a pilot is above or below the average flying hours of his age group. Now, when comparing the group located above the average with the group situated below the average, there is no longer a significant difference with respect to the frequency of back pain (Fig.16). This means, that the originally found relationship is only due to age and is generated by the fact that the parameters "Flying Hours" and "Frequency of Back Pain" are simultaneously correlated with age (8). This is again illustrated in a different way in Fig.17. When subdividing the entire collective into age categories of about the same size and when comparing the groups with and without back pain with respect to their number of flying hours within these categories, no significant difference is found in five of the six categories. There is only a significant difference in the age category between 26 and 30 years which, however, may not be overinterpreted because of the very low case number in this category (n = 11).

Another possibility to eliminate the "Age" parameter is to consider the flying hour stress per year and not the absolute number of flying hours. The straight lines drawn in Fig. 18 represent the annual flying hours stress separately for the group with and without back pain. Again no essential difference is found between both groups.

Now, Fig.19 shows a number of other factors which might possibly have an influence on the frequency of back pain. We were unable to find any significant correlation between the frequency of back pain and these factors in our collective. Sports activities are illustrated in detail in Fig. 20. As can be seen, there is no single sporting activity showing a significant difference between the number of pilots with and without back pain. Hence, it must be assumed that sports activities presently practiced in the examined collective obviously have no detrimental effects on the back nor can they be considered as a suitable prophylactic measure against back pain.

Finally we were interested in the attitude the pilots have relating to the question of possible health damages as a result of flying duties. As shown in Fig. 21 exactly half of the pilots questioned have the impression, that such noxious effects are present. We could not prove significant differences between the jet- and prop-group, however, distinctly between the groups with and without back pain (Fig. 22).

We searched for possible causes for this opinion (Fig.23). In doing so it is interesting to note that no connection can be construed with the majority of factors, which, according to our assessment constitute the essential causes for uncomfortable sensations in flight. Finally, a noxious effect is only attributed to G-forces and the stress caused by duration of sitting.

The question, whether they would still choose a flying career if they had to make the decision again was answered in the affirmative by 92.9% of the pilots without pain but only by 87% of the pilots with pain (Fig. 24). While the difference is not statistically significant, a certain tendency is nevertheless evident.

CONCLUSIONS

1. A causal connection between frequency of back pain and flying hours stress can not be verified.
2. The frequency of back pain is distinctly age-dependent and hence may be traced to completely normal signs of attrition of the ageing process.
3. Back pain constitutes a considerable subjective impairment not only for helicopter pilots but also for jet- and prop-pilots. The frequency of complaints of 47.4% found in jet-pilots lies above the value of approximately 30% known so far (1,4). This may be due to the fact that former studies did not differentiate between pilots with a purely reconnaissance mission and pilots having a combat mission. To obtain expressive results future studies will have to consider the mission profiles.
4. The sitting posture is one of the most important stress factors on the body. As part of the design of pilots seats all conceiveable measures should be taken which are appropriate to avoid an unstable spinal posture. In particular a too strong pelvis tilt to the rear should be prevented in order to reduce static muscle work and strain on intervertebral disks to a minimum.
5. A fitness and compensation sports training depending on the flying assignment should be developed for the individual pilot groups. In this context the specific strain on the spinal column should be considered to initiate physical training methods which are actually suitable and through which we can achieve a significant reduction of the frequency of back pain.
6. When investigating the connection between flying stress and damages to the spine the age factor must be eliminated through a procedure, e.g. as applied by us, since otherwise strongly misleading results are obtained.
7. As soon as verified results on a more or less possible interrelationship between flying stress and spinal damages are available, detailed and realistic information should be passed on to pilots. This is very important because of the fact that at the present time there is a widespread negative attitude concerning the problem of possible health damages. And this may have an essential impairment on flying motivation.

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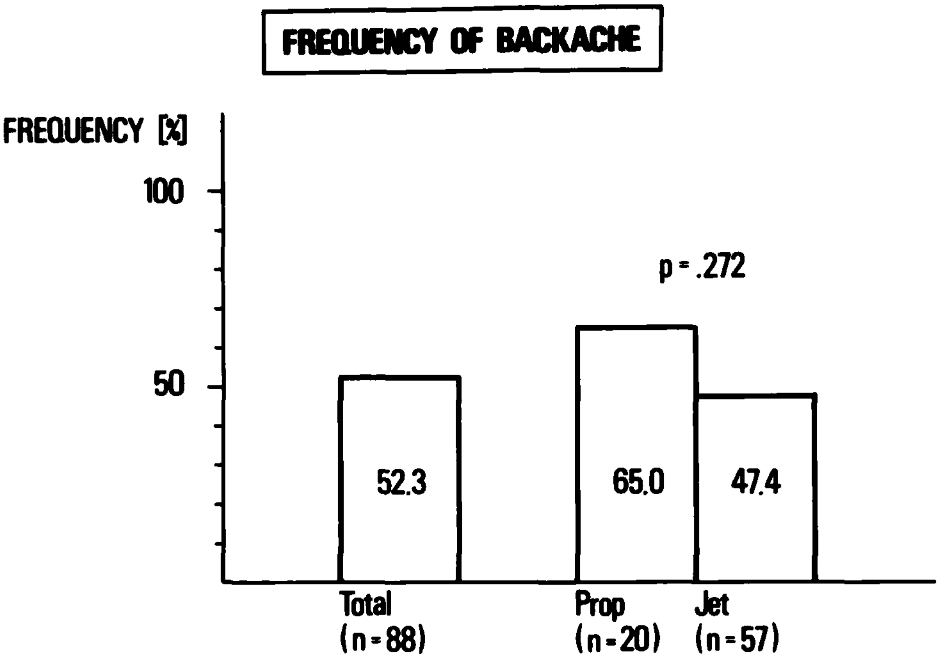
FREQUENCY OF BACKACHE
FREQUENCY [%]
100
50
p = .272
52.3
65.0
47.4
Total (n=88)
Prop (n=20)
Jet (n=57)

Fig. 1

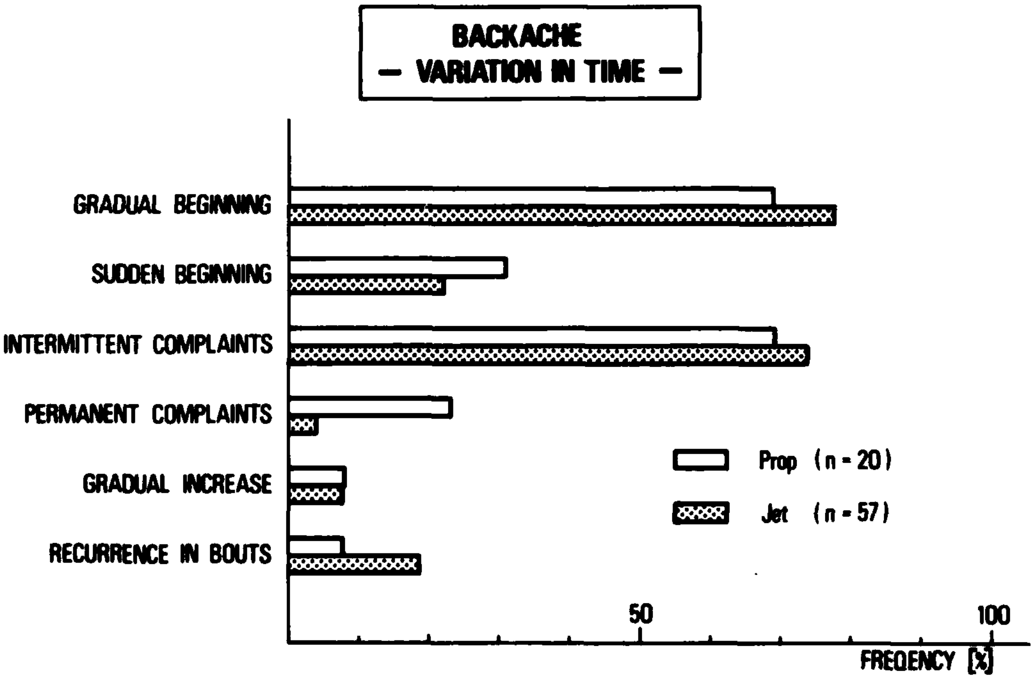
BACKACHE
— VARIATION IN TIME —
GRADUAL BEGINNING
SUDDEN BEGINNING
INTERMITTENT COMPLAINTS
PERMANENT COMPLAINTS
GRADUAL INCREASE
RECURRENCE IN BOUTS
Prop (n = 20)
Jet (n = 57)
50
100
FREQENCY [%]

Fig. 2

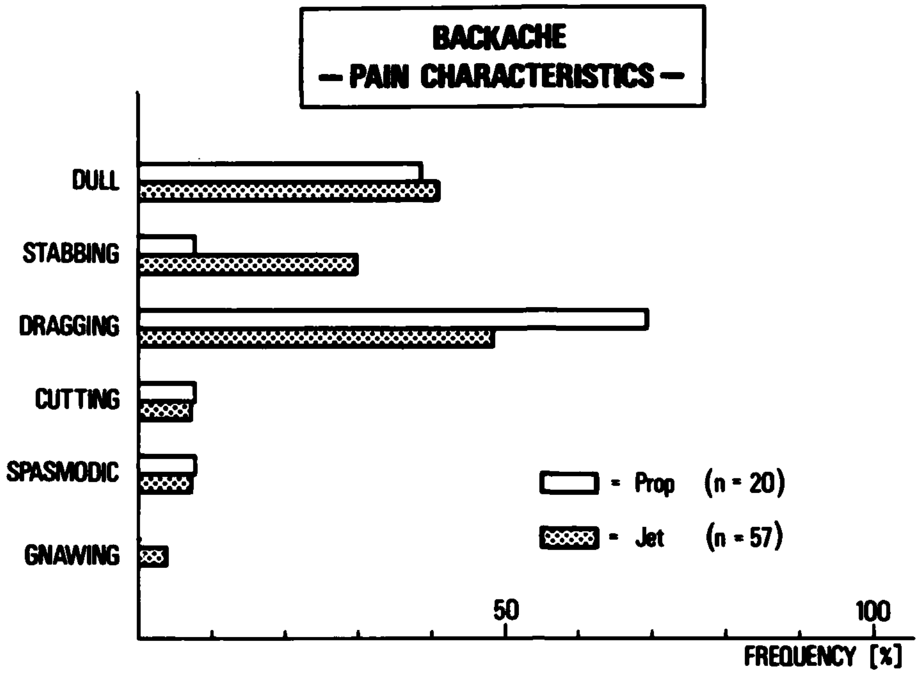
BACKACHE
– PAIN CHARACTERISTICS –
DULL
STABBING
DRAGGING
CUTTING
SPASMODIC
GNAWING
□ = Prop (n = 20)
▨ = Jet (n = 57)
50
100
FREQUENCY [%]

Fig. 3

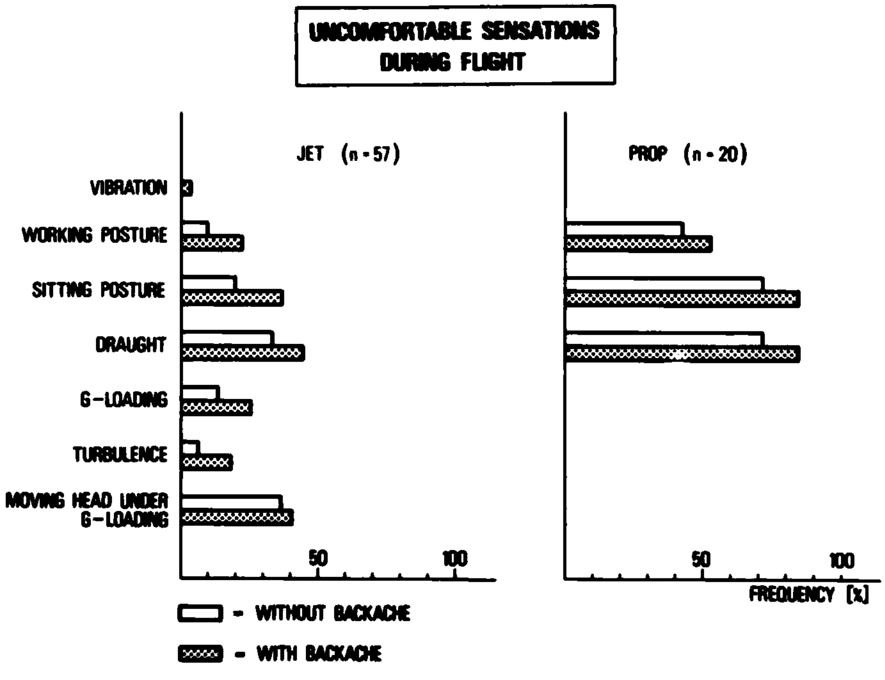
UNCOMFORTABLE SENSATIONS
DURING FLIGHT
JET (n = 57)
PROP (n = 20)
VIBRATION
WORKING POSTURE
SITTING POSTURE
DRAUGHT
G-LOADING
TURBULENCE
MOVING HEAD UNDER
G-LOADING
50
100
50
100
FREQUENCY [%]
□ = WITHOUT BACKACHE
▨ = WITH BACKACHE

Fig. 4

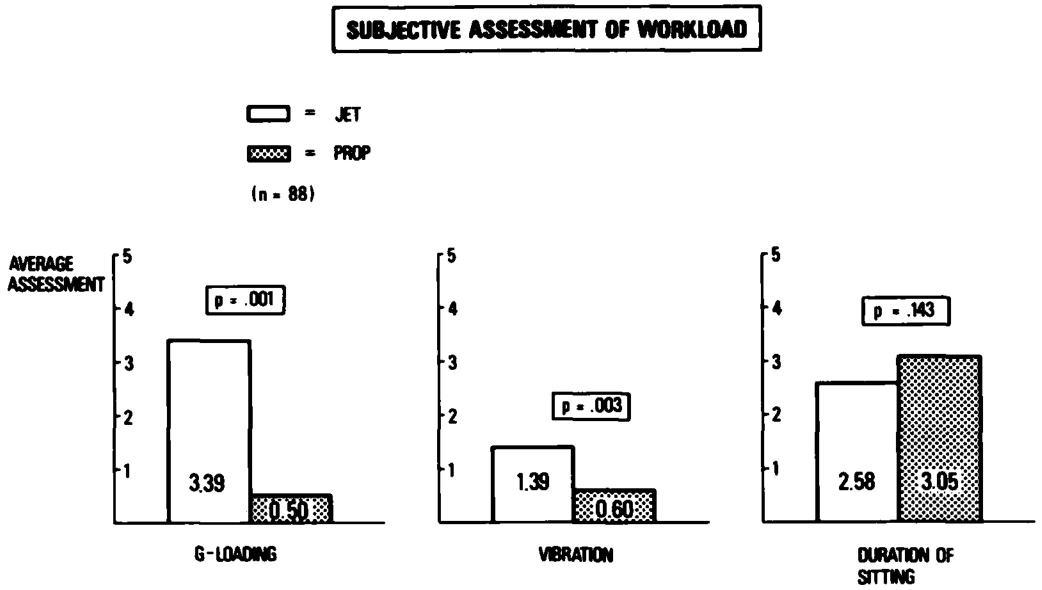
SUBJECTIVE ASSESSMENT OF WORKLOAD
▭ = JET
▨ = PROP
(n = 88)
AVERAGE ASSESSMENT
5
4
3
2
1
p = .001
3.39
0.50
G-LOADING
p = .003
1.39
0.60
VIBRATION
p = .143
2.58
3.05
DURATION OF SITTING

Fig. 5

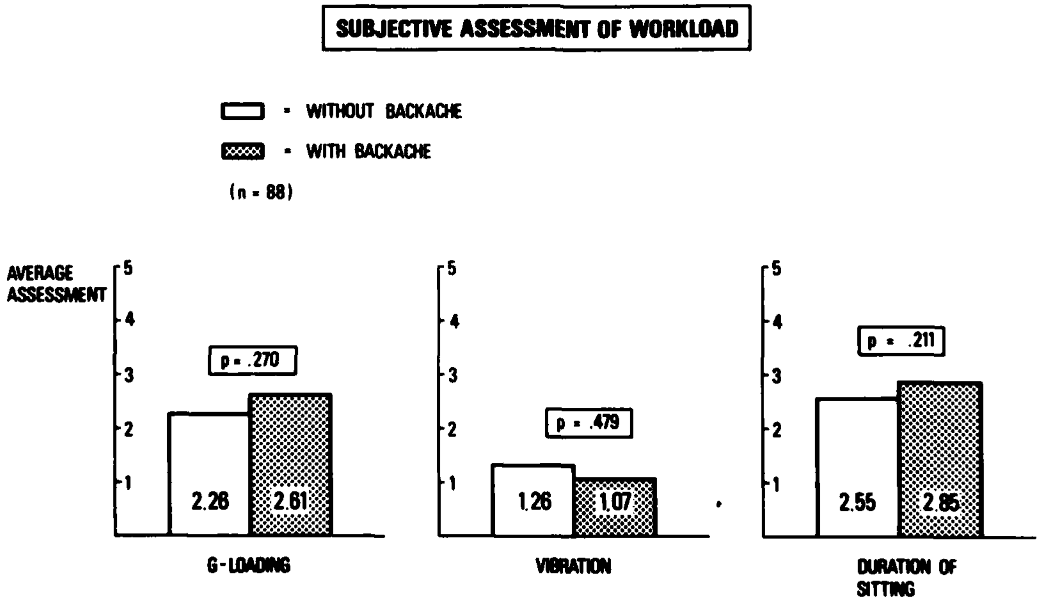
SUBJECTIVE ASSESSMENT OF WORKLOAD
▭ = WITHOUT BACKACHE
▨ = WITH BACKACHE
(n = 88)
AVERAGE ASSESSMENT
5
4
3
2
1
p = .270
2.26
2.61
G-LOADING
p = .479
1.26
1.07
VIBRATION
p = .211
2.55
2.85
DURATION OF SITTING

Fig. 6

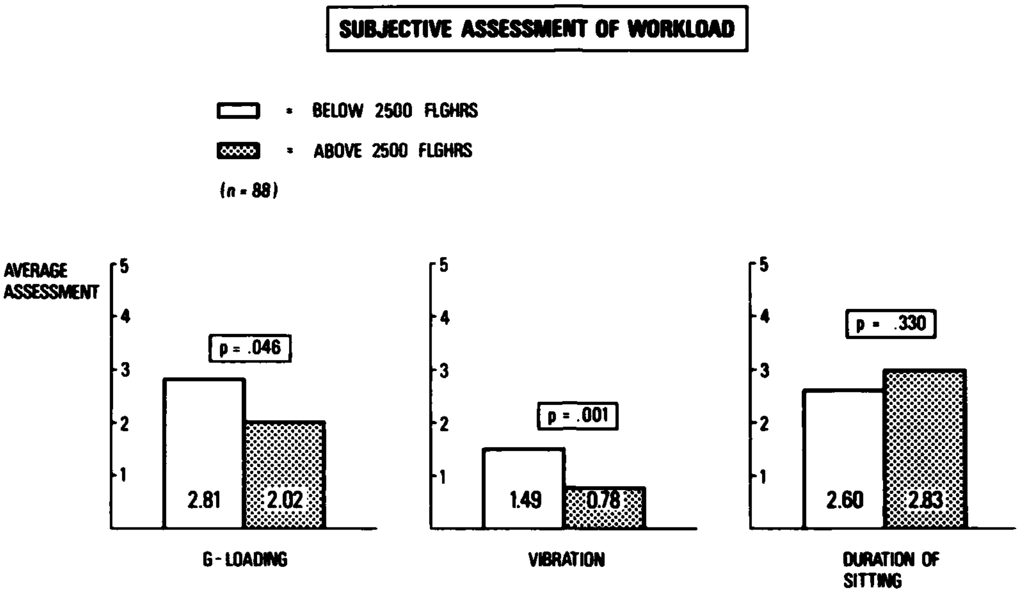
SUBJECTIVE ASSESSMENT OF WORKLOAD
▭ = BELOW 2500 FLGHRS
▨ = ABOVE 2500 FLGHRS
(n = 88)
AVERAGE ASSESSMENT
1
2
3
4
5
p = .046
2.81
2.02
G-LOADING
p = .001
1.49
0.78
VIBRATION
p = .330
2.60
2.83
DURATION OF SITTING

Fig. 7.

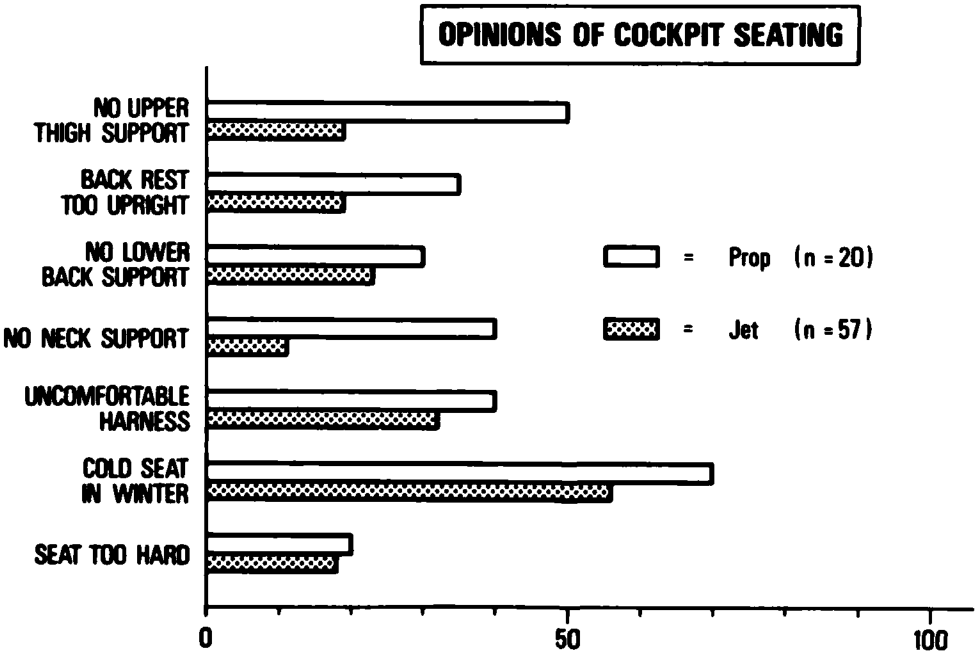
OPINIONS OF COCKPIT SEATING
NO UPPER THIGH SUPPORT
BACK REST TOO UPRIGHT
NO LOWER BACK SUPPORT
NO NECK SUPPORT
UNCOMFORTABLE HARNESS
COLD SEAT IN WINTER
SEAT TOO HARD
▭ = Prop (n = 20)
▨ = Jet (n = 57)
0
50
100

Fig. 8

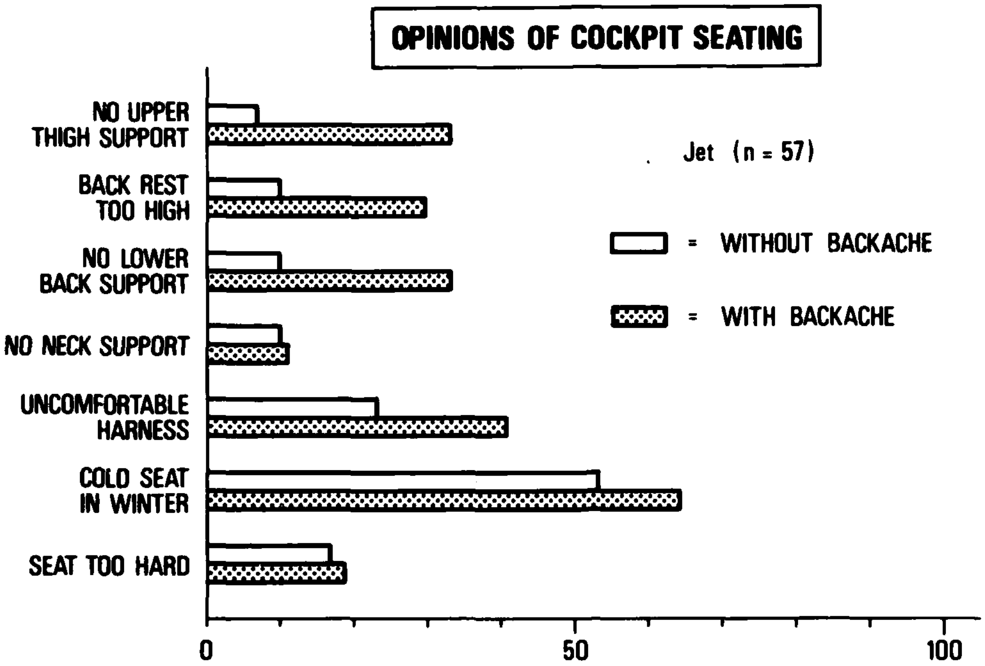
OPINIONS OF COCKPIT SEATING
NO UPPER THIGH SUPPORT
BACK REST TOO HIGH
NO LOWER BACK SUPPORT
NO NECK SUPPORT
UNCOMFORTABLE HARNESS
COLD SEAT IN WINTER
SEAT TOO HARD
Jet (n = 57)
▭ = WITHOUT BACKACHE
▨ = WITH BACKACHE
0
50
100

Fig. 9

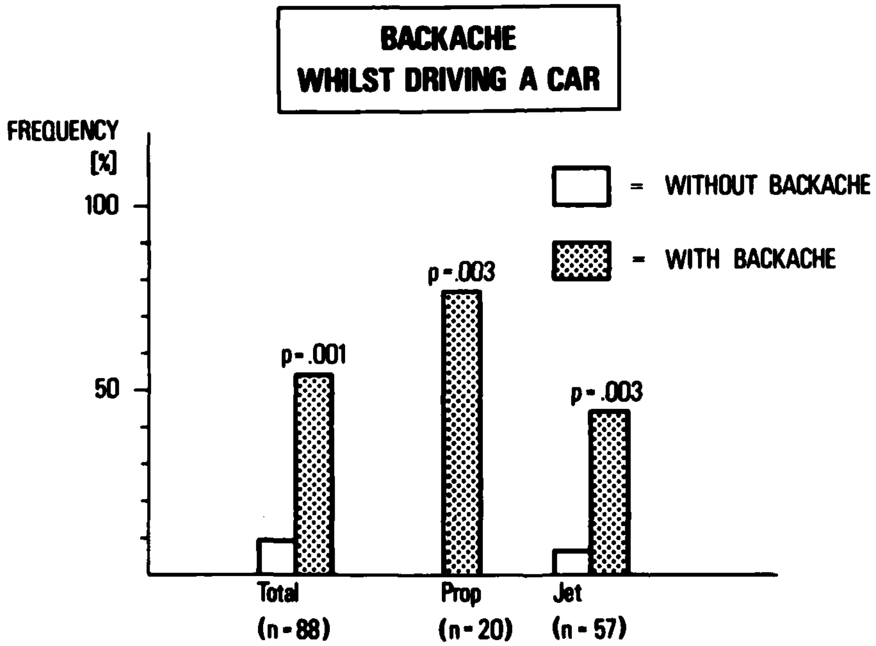
BACKACHE WHILST DRIVING A CAR
FREQUENCY [%]
100
50
▭ = WITHOUT BACKACHE
▨ = WITH BACKACHE
p=.001
p=.003
p=.003
Total (n=88)
Prop (n=20)
Jet (n=57)

Fig. 10

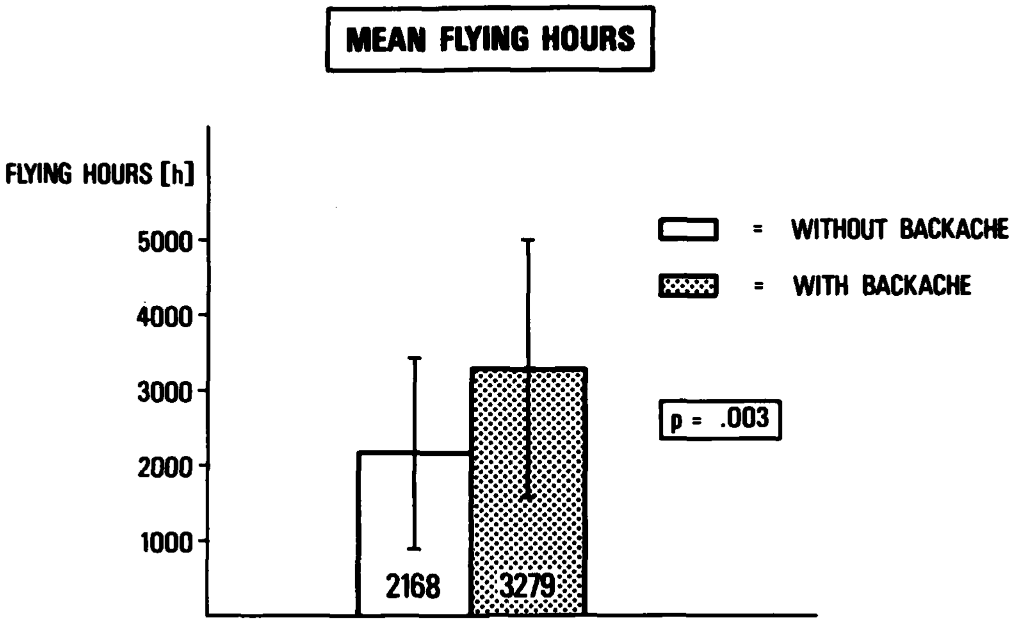
MEAN FLYING HOURS
FLYING HOURS [h]
5000
4000
3000
2000
1000
2168
3279
▭ = WITHOUT BACKACHE
▨ = WITH BACKACHE
p = .003

Fig. 11

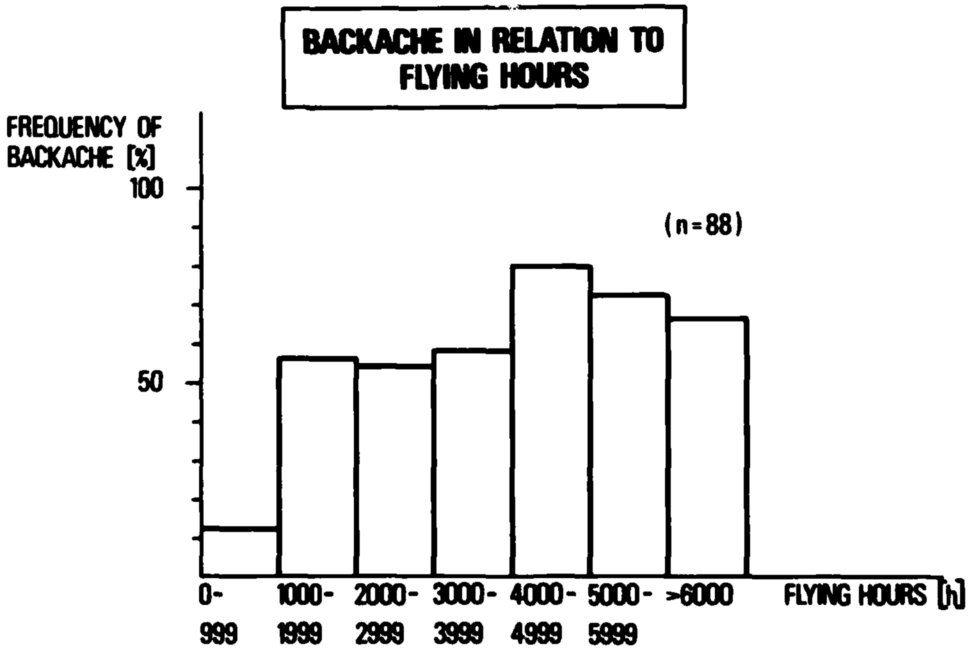
BACKACHE IN RELATION TO FLYING HOURS
FREQUENCY OF BACKACHE [%]
100
50
(n=88)
0-999
1000-1999
2000-2999
3000-3999
4000-4999
5000-5999
>6000
FLYING HOURS [h]

Fig. 12

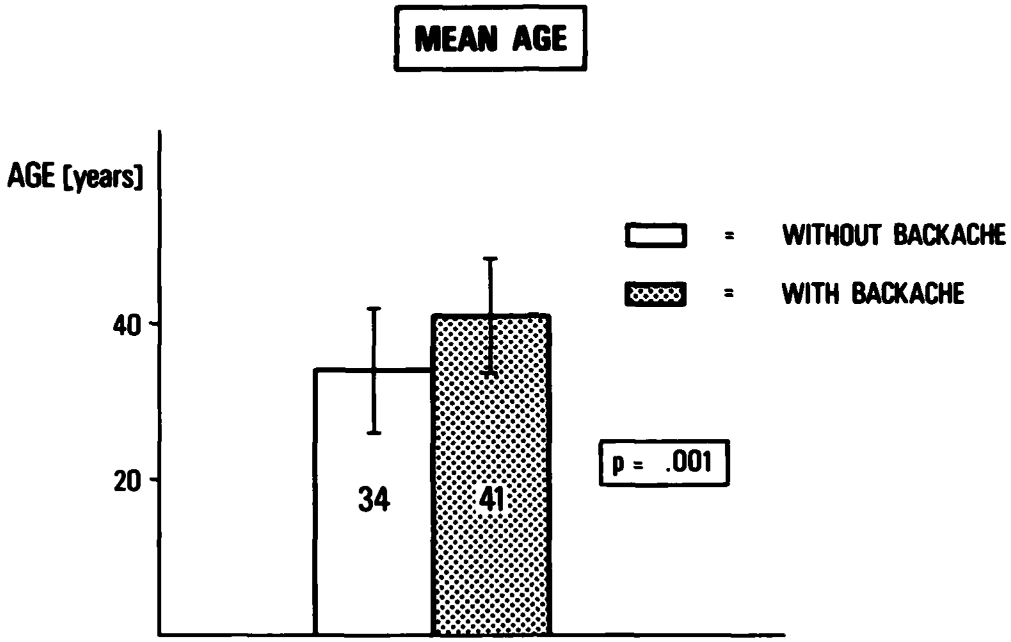
MEAN AGE
AGE [years]
40
20
34
41
= WITHOUT BACKACHE
= WITH BACKACHE
p = .001

Fig. 13

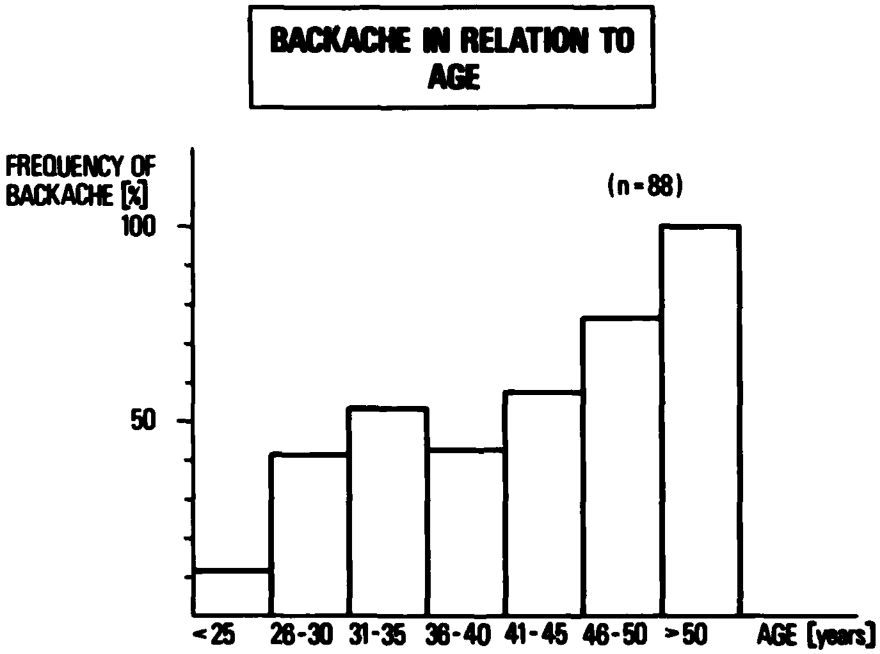
BACKACHE IN RELATION TO AGE
FREQUENCY OF BACKACHE [%]
100
50
(n=88)
<25
26-30
31-35
36-40
41-45
46-50
>50
AGE [years]

Fig. 14

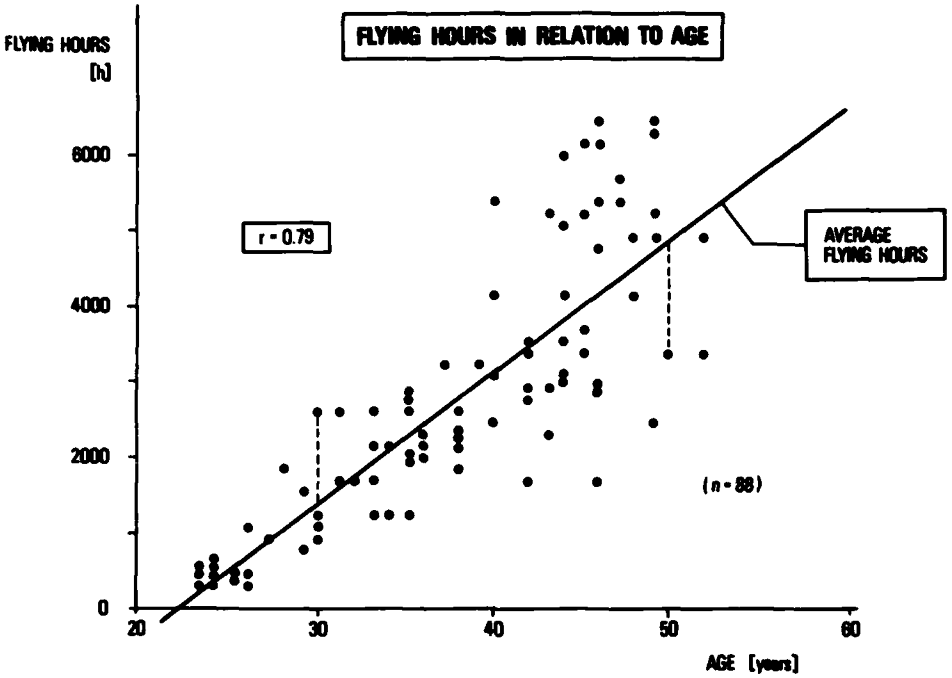
FLYING HOURS IN RELATION TO AGE
FLYING HOURS [h]
6000
4000
2000
0
20
30
40
50
60
AGE [years]
r = 0.79
AVERAGE FLYING HOURS
(n = 88)

Fig. 15

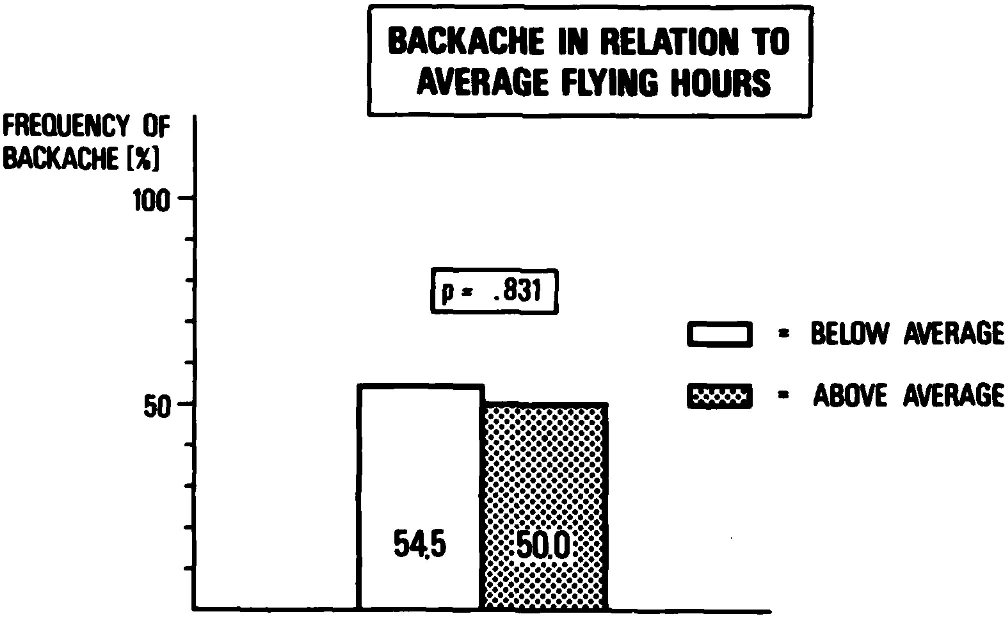
BACKACHE IN RELATION TO AVERAGE FLYING HOURS
FREQUENCY OF BACKACHE [%]
100
50
p = .831
54.5
50.0
= BELOW AVERAGE
= ABOVE AVERAGE

Fig. 16

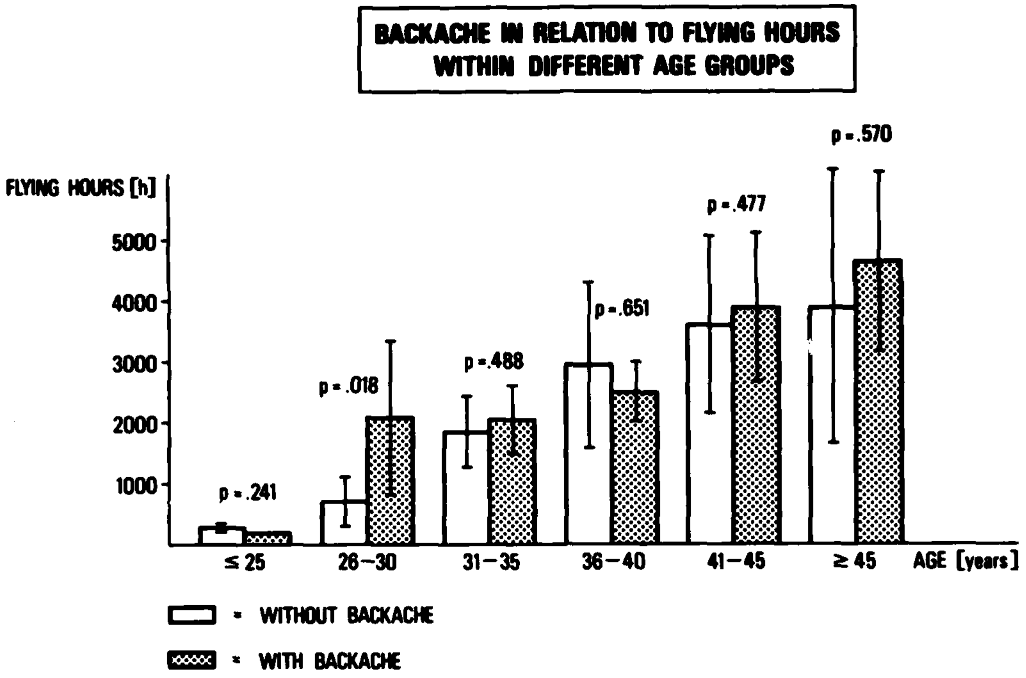
BACKACHE IN RELATION TO FLYING HOURS WITHIN DIFFERENT AGE GROUPS
FLYING HOURS [h]
5000
4000
3000
2000
1000
p = .241
p = .018
p = .488
p = .651
p = .477
p = .570
≤ 25
26–30
31–35
36–40
41–45
≥ 45
AGE [years]
▭ = WITHOUT BACKACHE
▨ = WITH BACKACHE

Fig. 17

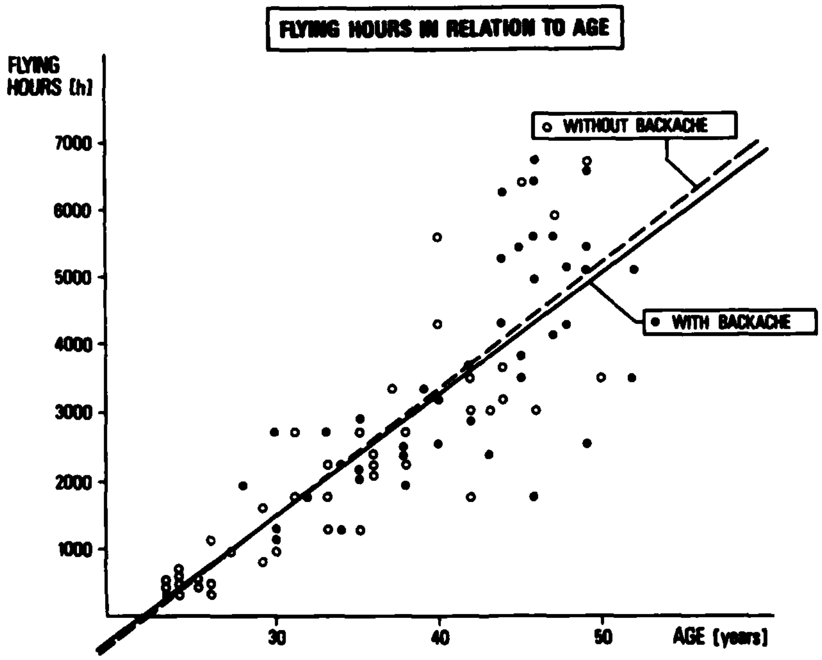
FLYING HOURS IN RELATION TO AGE
FLYING HOURS [h]
7000
6000
5000
4000
3000
2000
1000
30
40
50
AGE [years]
○ WITHOUT BACKACHE
● WITH BACKACHE

Fig. 18

FACTORS WITH POSSIBLE INFLUENCE ON THE FREQENCY OF BACKACHE

FREQUENCY OF EJECTON SEAT TRAINING	∅ (p = .443)
PRIVATE FLYING HOURS	∅ (p = .324)
SPORTS BEFOR BEGINNING FLYING ACTIVITY [hours per week]	∅ (p = .759)
SPORTS AFTER BEGINNING FLYING ACTIVITY [hours per week]	∅ (p = .637)
OVERWEIGHT	∅ (p = .910)
AIR ACCIDENT	∅ (p = .999)

∅ = NO SIGNIFICANT CORRELATION

Fig. 19

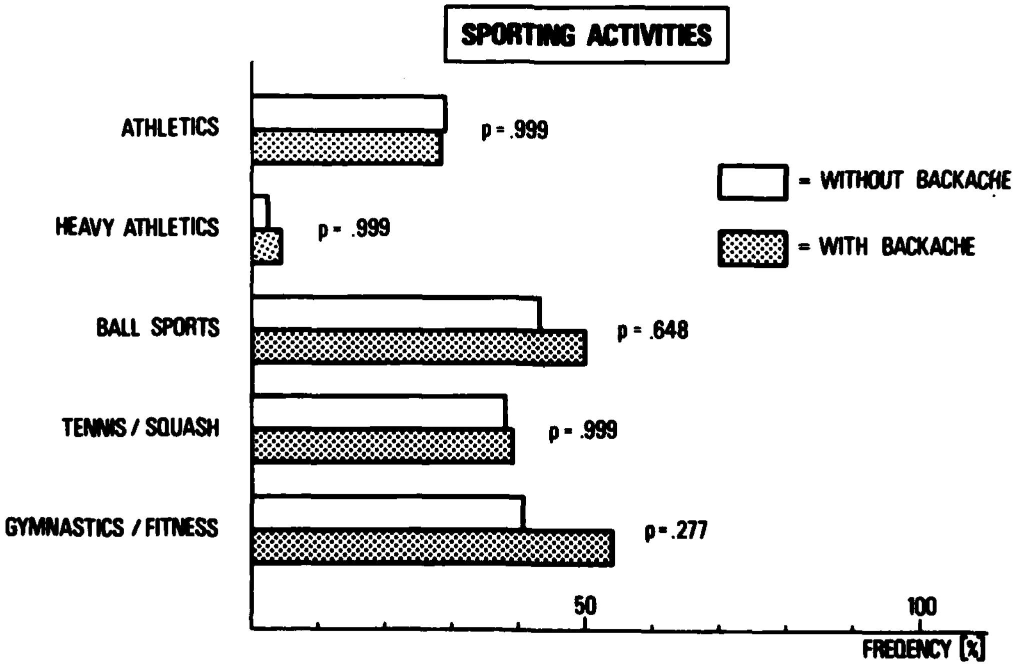

Fig. 20

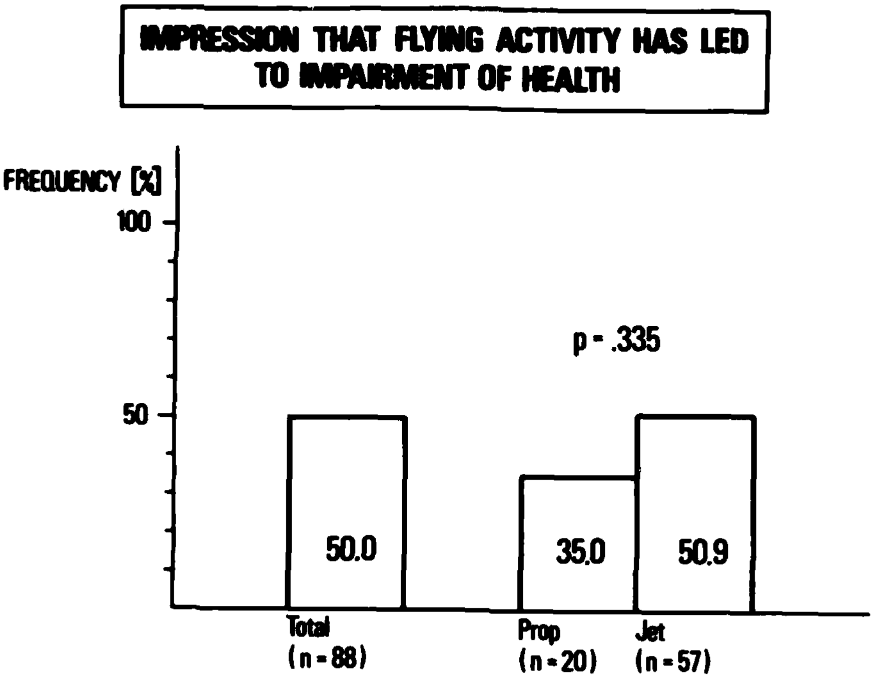
IMPRESSION THAT FLYING ACTIVITY HAS LED TO IMPAIRMENT OF HEALTH
FREQUENCY [%]
100
50
p = .335
50.0
35.0
50.9
Total (n = 88)
Prop (n = 20)
Jet (n = 57)

Fig. 21

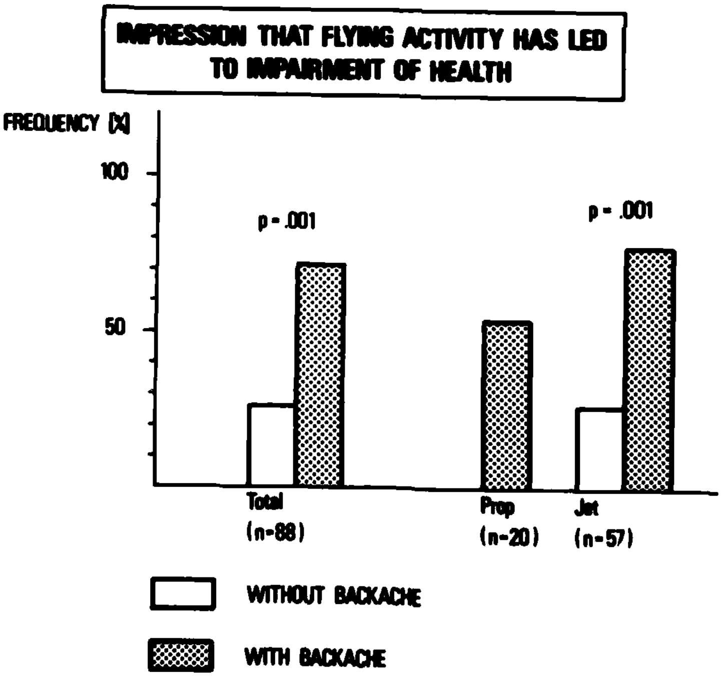
IMPRESSION THAT FLYING ACTIVITY HAS LED TO IMPAIRMENT OF HEALTH
FREQUENCY [%]
100
50
p = .001
p = .001
Total (n=88)
Prop (n=20)
Jet (n=57)
WITHOUT BACKACHE
WITH BACKACHE

Fig. 22

IMPRESSION THAT FLYING ACTIVITY HAS LED TO IMPAIRMENT OF HEALTH

FACTORS WHICH MAY INFLUENCE
THE PERSONAL ATTITUDE:

WORKING POSTURE	∅
SITTING POSTURE	∅
DRAUGHT	∅
TURBULENCE	∅
MOVING HEAD UNDER G-LOADING	∅
ASSESSMENT OF G-LOADING	+ (p = .025)
ASSESSMENT OF VIBRATION	∅
ASSESSMENT OF DURATION OF SITTING	+ (p = .044)

+ = POSITIVE CORRELATION

∅ = NO SIGNIFICANT CORRELATION

Fig. 23

NUMBER OF AIRCREW ASKED RETROSPECTIVELY IF THEY WOULD STILL ELECT TO BE AIRCREW

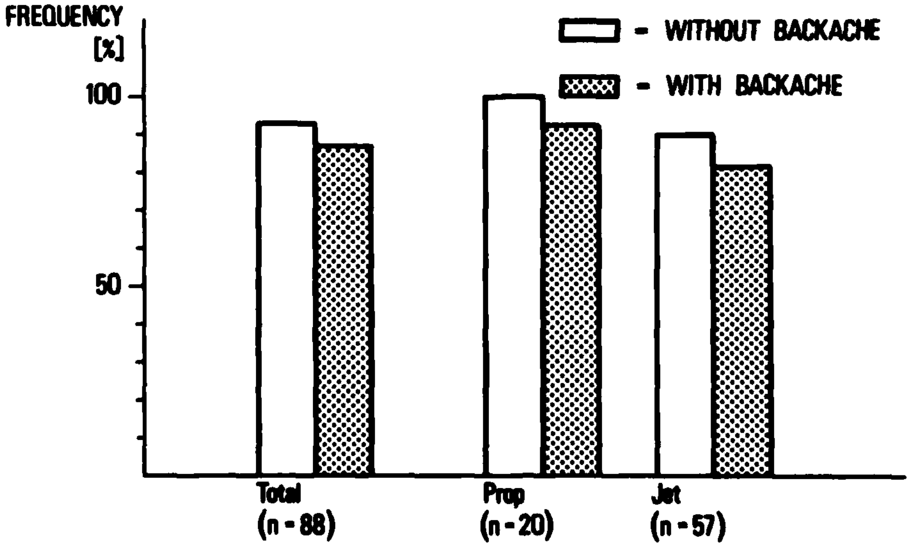

Fig. 24

DISCUSSION

KLAVENESS, NO: Did you consider whether or not back pain in your pilcts was related to flying?

THOMA, GE: Our question was "To what extent did backache occur during flight or in relation to a particular flying mission?" We will extend our studies in the future and make the question more specific, so that we will get information about pain during flight; especially that pain which may impair concentration or reduce the assurance of completing a mission. For this study, we did not ask questions in a very detailed manner.

KLAVENESS, NO: So the figures that you presented relate to all types of back pain, flying and non-flying?

THOMA, GE: Yes, most of the pilots experiencing back pain stated that they had pain predominantly in the lumbar region.

KLAVENESS, NO: You have answered my question. In the case of the jet pilots, what aircraft were they flying and what ejection seats were fitted into these aircrafts?

THOMA, GE: It's a very small aircraft. It's called the Alpha jet and it's an aircraft for training young students who have returned from their initial flight training in the USA and are now obtaining some specialization in European airspace. The prop planes were the Piaggio 149 and the Dornier 28.

BACK DISCOMFORT IN U.S. ARMY HELICOPTER AIRCREW MEMBERS

by
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SUMMARY

The relationship of back discomfort to military helicopter flight operations was studied in this questionnaire survey of 802 U.S. Army helicopter pilots. Of the surveyed population, 584 (72.8%) pilots reported experiencing back discomfort while flying over the last two years. The discomfort generally was described as a dull ache confined to the lower back, with a mean onset time of 88 minutes into a mission. The relationship of reporting the pain to physical characteristics, past medical history, physical activity, and aviation experience is discussed. For over half of the respondents (50.1%), the pain was transient (less than 24 hours duration), resolving rapidly after discontinuing a provoking flight. Nevertheless, there was a significant number of aviators who reported persistent symptoms lasting over 48 hours (14.5%). Possible etiologies of the pain for both groups, as well as potential methods of prevention are discussed.

A high incidence of back pain in helicopter flight crews has been documented in numerous studies, primarily by European authors over the last 25 years (Delahaye, 1982; Fitzgerald, 1968; Fitzgerald, 1972; Gearhart, 1978; Rance, 1974; Schulte-Wintrop, 1978; Sliosberg, 1962). Incidences have varied widely in these reports apparently depending on the population studied, sample size, and the type and duration of missions typically flown by the sample population.

The U.S. Army operates the largest helicopter fleet in the free world, and Army flight surgeons long have suspected that a large proportion of Army helicopter pilots complain of back pain associated with their flying duties. If, in fact, a large proportion of Army pilots suffer from back pain while flying or as a result of flying, this pain could be having a significant impact on aviation operational readiness, effectiveness, and flight safety. Consequently, a questionnaire survey of Army helicopter pilots was conducted to determine the extent of the problem, the nature of the pilots' complaints, and associated risk factors.

MATERIALS AND METHODS

A 33-question survey was prepared which covered various aspects of pilots' medical history, aviation experience, and social history. It also sought responses as to whether or not pilots had experienced back discomfort while flying at any time during the preceding two years. For those who answered affirmatively, more details were sought about frequency of occurrence, initial onset, duration of symptoms, intensity of discomfort, location of discomfort, radiation of symptoms, and the extent such symptoms were related to various aircraft types.

A cover letter attached to each questionnaire requested cooperation and guaranteed each respondent anonymity. The questionnaires were sent to four U.S. Army aviation installations where a previously-briefed individual administered the survey. This individual was either a flight surgeon or an aviation safety officer who was instructed to conduct the survey during a regularly-scheduled aviation safety briefing. To avoid generating unnecessary adverse reaction toward the survey, pilots were not assembled specifically to answer the questionnaire. Respondents received no instructions other than those contained in the cover letter and the questionnaire itself. The pilots were requested to turn in a blank questionnaire if they did not feel they could answer the questions fully and honestly. The questionnaire required 10 to 15 minutes.

Completed questionnaires were returned to the authors and each response coded. Data analysis was done with a VAX 11/780 computer using the Statistical Package for the Social Sciences (SPSS) computer program (Nie, 1975). For continuous variables whose distribution was reasonably normal, such as respondent age, height, and weight, t-tests were performed. Kolmolgorov-Smirnov tests were used for variables whose distributions departed markedly from normal. This was the case for measures of flight experience which were extremely positively skewed. Responses requiring only frequency or classification analysis were analyzed using chi-square tests.

RESULTS

Of 1,100 questionnaires mailed to the four Army installations, 802 completed questionnaires were returned for a 72.9 percent response rate. Of the 802 respondents, 584 (72.8%) reported they had experienced one or more episodes of "back discomfort" while flying helicopters over the last two years, while 218 (27.2%) denied having problems. These two groups formed the basis of this study and are referred to as the "pain" and "no pain" groups respectively.

Table I summarizes the means (±1 S.D.) for the age, height, weight, waist, flight hours, and years flight experience for both groups. There were no significant differences in these characteristics between the groups except for total rotary-wing flight hours.

TABLE I

GENERAL PILOT CHARACTERISTICS (MEAN ±S.D.)
FOR PAIN AND NO PAIN GROUPS

	Pain		No Pain		p-Value
Age (Years)	30.8	(±6.3)	31.3	(±6.3)	0.283
Height (inches)	70.5	(±3.2)	70.8	(±3.8)	0.241
Weight (pounds)	174.1	(±20.0)	174.3	(±20.2)	0.889
Waist (inches)	33.4	(±3.4)	34.4	(±8.6)	0.654
Years Flight	6.9	(±6.0)	6.8	(±6.0)	0.436
Total Flight Hours	2107.3	(±2687.6)	1728.9	(±2135.3)	0.747
Fixed-Wing Hours	593.2	(±1507.7)	654.7	(±2466.9)	0.970
Rotary-Wing Hours	1824.8	(±1977.8)	1491.7	(±1772.0)	0.0001

The history of sports participation and other physical activities, during adolescence and currently, was compared for the pain and no pain groups. There was no association between the reporting of pain during flight and participation in any particular sport or physical activity, either previously or currently. To compare the two extremes of physical activity, those who had reported that they had never participated in any sports or physical activities were compared with those who reported that they currently participated in three or more sports or physical activities. There was no significant difference between these two groups in the reporting of pain while flying. Similarly, there also was no statistical difference in the self-reported physical condition between the pain and no pain groups (Table II).

TABLE II

SELF-REPORTED PHYSICAL CONDITION FOR
PAIN AND NO PAIN GROUPS

	Excellent	Good	Poor
Pain	236 (40.7%)	338 (58.3%)	6 (1.0%)
No Pain	103 (47.7%)	113 (52.3%)	0 (0%)

$p > 0.05$

Previous medical history and its relationship to the reporting of back discomfort during flight also was explored. It was interesting that reporting a "previous back problem" was not associated significantly with experiencing pain during flight (Table III), while there was a highly significant association ($p < 0.0025$) of a "previous back injury with symptoms lasting longer than 24 hours" with the reporting of pain while flying (Table III). Not surprisingly, pilots having sought medical attention for a back problem ($p < 0.001$) and those having missed work because of a back problem ($p < 0.025$) also were significantly associated with the reporting of pain while flying. Only 14.4 percent of the pain group attributed symptoms to a specific past injury, and 2.2 percent of them reported they required a medical waiver to remain on flight status. There was no association between reported smoking history, either in terms of whether a respondent smoked or not or total pack-years, and the occurrence of back pain.

An attempt was made to characterize symptoms reported by the 584 aviators who reported back discomfort while flying. Figure 1 depicts where the discomfort most frequently occurred for each individual. Seventy percent of respondents most frequently experienced discomfort in the lower back. Discomfort in the buttocks (16.6%) was the next most frequently reported region, while relatively few pilots reported symptoms in other regions. Numbness in the legs was a frequent occurrence (34.4%), while only 4.3 percent of the pain group noted episodes of numbness in the arms. Respondents were asked to rate the intensity of the discomfort they experienced on a scale of one to nine, with one representing no pain and nine representing excruciating pain. Figure 2 shows a frequency distribution of their responses. The modal intensity was three with a mean response of 4.2. Therefore, the pain most pilots reported can be characterized as mild-to-moderate. Figure 3 depicts the frequency of flights during which the respondents experienced symptoms. There is a wide variation in reported frequencies and only 26 percent of respondents reported back pain symptoms on more than 50 percent of their flights. An observation that probably relates to this finding is that the mean duration of flight required to produce symptoms in the pain group was 88 minutes. Pilots were asked to rate the different types of aircraft they had flown as to their propensity to cause them back discomfort. Analysis of these data failed to show any significant association of the reporting of pain with any particular aircraft type.

TABLE III

RELATIONSHIP OF PAST MEDICAL HISTORY
TO THE REPORTING OF BACK PAIN DURING FLIGHT

	Previous Back Problems		Previous Back Injury		Sought Medical Advice		Lost Work Because of Back Pain	
	Yes	No	Yes	No	Yes	No	Yes	No
Pain	81 (13.9%)	503 (86.1%)	224 (38.4%)	360 (61.6%)	228 (39.0%)	356 (61.0%)	126 (21.6%)	458 (78.4%)
No Pain	40 (18.2%)	178 (81.8%)	58 (26.6%)	160 (73.4%)	54 (24.8%)	164 (75.2%)	31 (14.2%)	187 (85.8%)
	$p > 0.05$		$p < 0.005$		$p < 0.001$		$p < 0.05$	

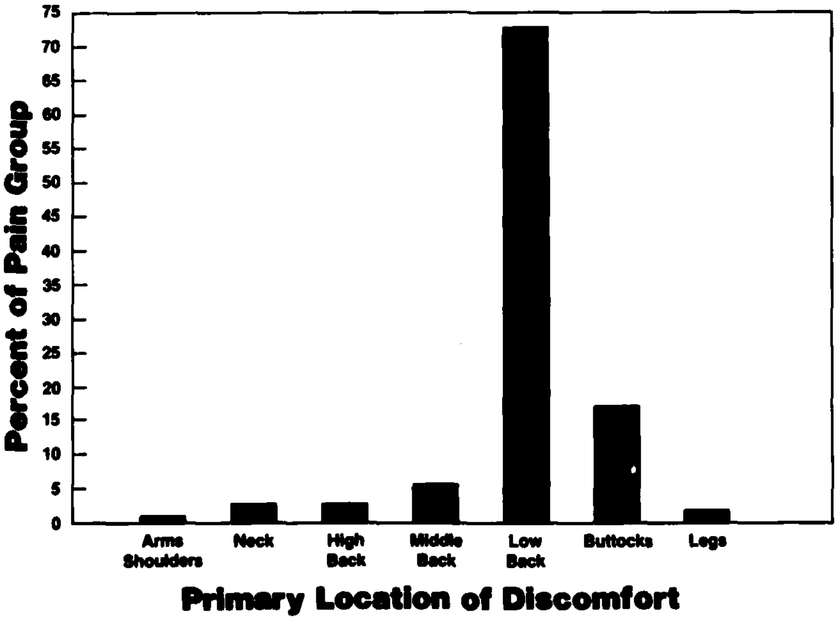

Figure 1. Histogram depicting where back discomfort most frequently occurred for each respondent who reported experiencing back discomfort during flight.

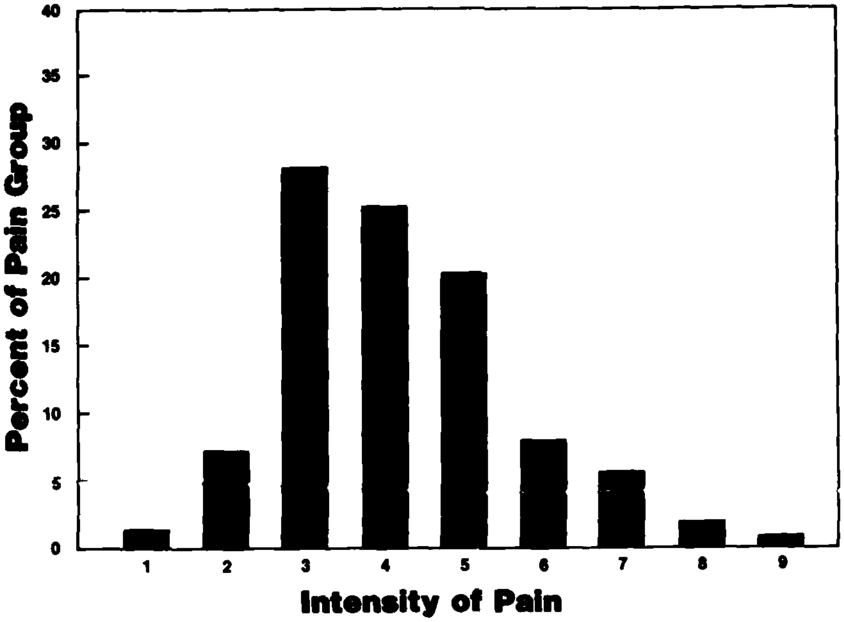

Figure 2. Histogram depicting the intensity of pain reported by respondents in the pain group. 1 = no pain; 9 = excruciating pain.

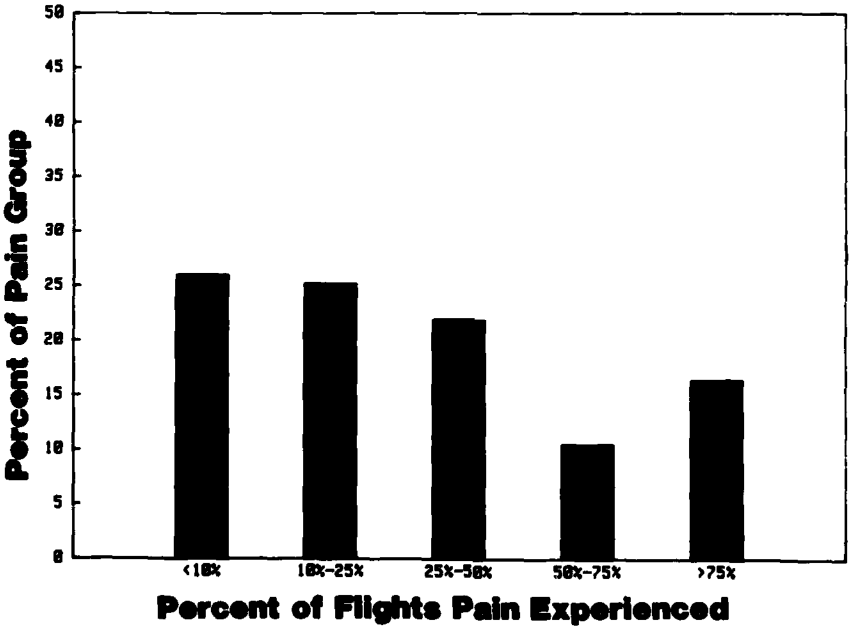

Figure 3. Histogram depicting percentage of missions during which each respondent in the pain group reported experiencing back discomfort.

The questionnaire required responses to a series of questions of how afflicted aviators tried to alleviate their symptoms. The results are summarized in Table IV. It is interesting that 28.4 percent admitted to rushing through one or more missions due to their back pain and 7.5 percent said they had refused a mission because of back pain. Most pilots (83.5%) said they frequently shifted their sitting positions, and about a third (32.7%) relinquished the controls to a copilot to help alleviate their pain. Additionally, 27.8 percent of the respondents reported they used an extra seat or lumbar cushion, and 22.9 percent stated they loosened their lap belts to help relieve discomfort.

TABLE IV

METHODS EMPLOYED TO ALLEVIATE SYMPTOMS

	No. of Respondents (%)*
Extra Seat Cushion	64 (11.0%)
Lumbar Pad	90 (16.8%)
Loosen Seatbelt	134 (22.9%)
Relinquish Controls to Copilot	191 (32.7%)
Rush Missions	166 (28.4%)
Refuse Missions	44 (7.5%)

* Represents percentage of the total pain group of 584 respondents. One individual may have employed several methods to alleviate his symptoms.

Another factor considered was the time in terms of total flight hours, that each pilot in the pain group first noted the onset of symptoms. Significantly, one-third of the aviators initially noted symptoms within their first 100 hours of flight and over half had symptoms by 300 hours (Figure 4). Pilots were asked to estimate how long their symptoms persisted after the end of a typical flight in which they became symptomatic. Figure 5 is a plot of the proportion of pilots remaining symptomatic versus hours postflight. It should be noted that symptoms are relatively transient for the majority of afflicted pilots. Half of the pilots were asymptomatic by 10 hours and only about one-third remained symptomatic longer than 24 hours. Nevertheless, there was a small group of pilots whose symptoms tended to persist several days. Approximately 14.5 percent remained symptomatic at 48 hours, and 8 percent reported they typically remained symptomatic over four days postflight.

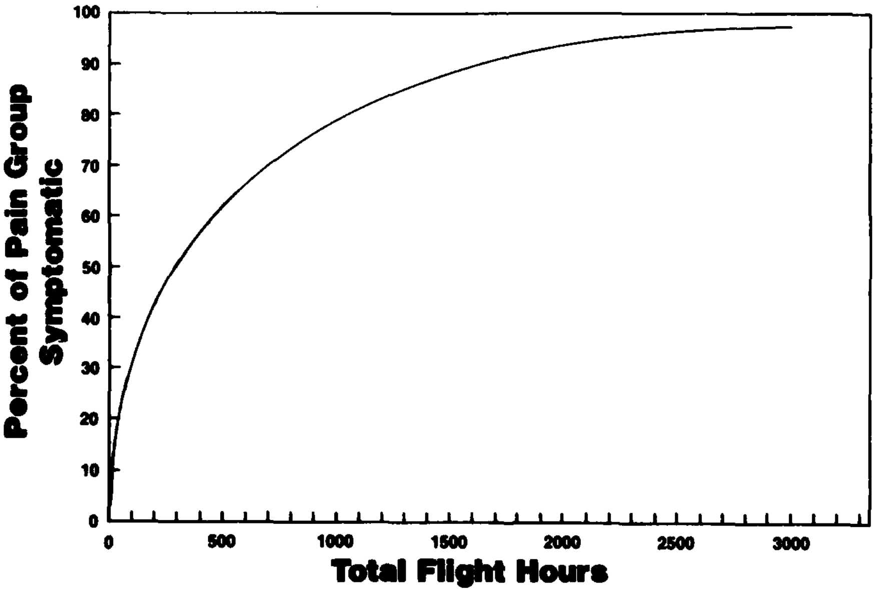

Figure 4. Graph showing the relationship between total flight hours and the initial onset of back symptoms for pilots who reported experiencing back discomfort during flight.

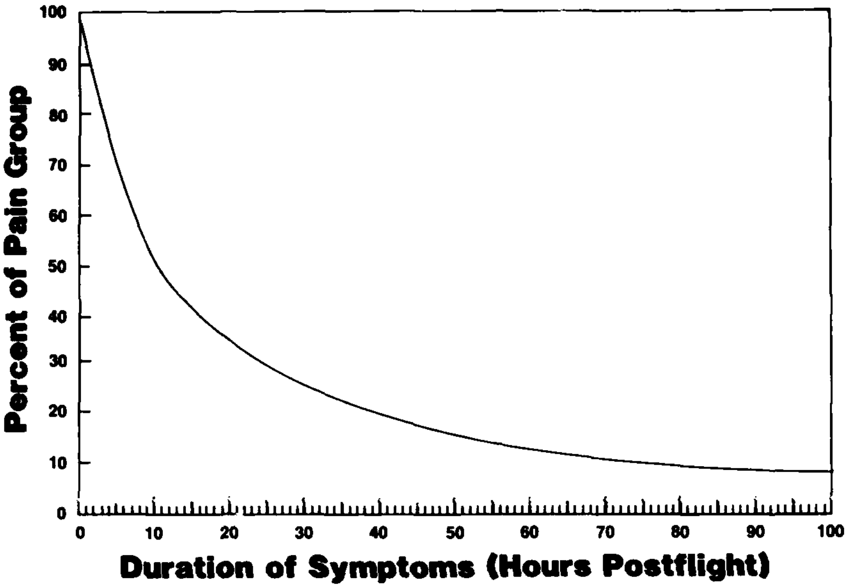

Figure 5. Graph showing the duration of symptoms in hours postflight versus the percentage of respondents remaining symptomatic.

The pilots reporting transient symptoms, defined as less than 24 hours, were compared with the group that reported persistent symptoms, defined as greater than 48 hours. This was done to detect systematic differences between the two groups that could lead to the identification of risk factors for having persistent symptoms. There were no significant differences in age, physical characteristics, or physical condition for the groups. Also, there was no significant difference in the time of initial onset of symptoms. Although the differences were not significant, the persistent pain group showed a slight tendency toward having more years on flight status ($p = 0.056$) than the transient group. However, the most distinct differences between the transient pain group and the persistent pain group were in the frequency and degree of symptoms they reported. The persistent pain group had symptoms more often ($p < 0.01$) and the intensity of the pain was significantly greater ($p < 0.001$), than the transient symptom group. Similarly, the persistent pain group sought medical advice more frequently ($p < 0.001$), refused missions more often ($p < 0.001$), and rushed through missions more often ($p < 0.001$) than did the transient pain group. The persistent pain group also reported a higher rate of previous injury ($p < 0.001$), a higher prevalence of leg numbness ($p < 0.01$), and a higher prevalence of pilots flying with a medical waiver ($p < 0.02$).

DISCUSSION

The high prevalence of back pain (72.8%) in this survey of 802 U.S. Army helicopter pilots is reasonably consistent with findings in surveys of European military helicopter aircrews (Delahaye, 1982; Fitzgerald, 1968; Fitzgerald, 1972; Sliosberg, 1962). However this rate represents a dramatic departure from the prevalence of back pain reported in the general population where rates are considerably less than 30 percent (Svensson, 1983; Svensson, 1982). Consequently, there appears to be a marked association between helicopter flying and the occurrence of back pain in aircrews.

Despite the high prevalence of back symptoms in the population studied, nearly a third of the respondents denied ever experiencing back discomfort while flying. This group was compared to the pain group to try to identify potential risk factors for developing back pain while flying. The only positively correlated factors identified were having had a previous back injury with symptoms lasting longer than 24 hours, having sought medical attention for a back ailment, and having missed work due to a back ailment. The pain group also had significantly more rotary-wing flight hours. Age, physical characteristics, total flight hours, years on flight status, sports participation, self-reported physical condition, smoking history, and having previous back problems were not associated with a statistically higher risk for experiencing back problems as has been shown in other studies (Delahaye, 1982; Fitzgerald, 1968; Fitzgerald, 1972; Frymoyer, 1978; Frymoyer, 1983; Gearhart, 1978; Sliosberg, 1962; Svensson, 1982; White, 1982). Clearly, there are other risk factors, which this survey failed to identify, that determine whether a particular individual will be subject to back discomfort while flying helicopters.

The typical pain syndrome described by pilots responding to the survey was a dull ache confined to the lower back that appeared about 88 minutes into a mission. The pain increased slowly as the flight progressed and was not reduced by shifting position or relinquishing the controls to a copilot. For most respondents, the pain only began to subside upon termination of the flight. The onset of pain appears to be a threshold phenomenon requiring a certain duration mission before symptoms appear for a specific individual. Since a large proportion of missions are shorter than the mean onset time of 88 minutes, afflicted aviators will not necessarily experience symptoms on every flight. This may explain the wide variation in reported frequency of symptoms (Figure 3).

The intensity of pain noted by afflicted aviators on a digital pain scale (Figure 2) can, in general, be described as mild-to-moderate. However, the pain was sufficiently intense for many aviators to have had an adverse effect on their performance (Table IV). It is rather disturbing that 28.4 percent of afflicted aviators admitted to rushing through missions because of back pain, and 7.5 percent admitted actually refusing missions because of pain. Either situation has a potentially adverse impact on mission accomplishment, and the former can adversely affect safety. Furthermore, these figures are probably somewhat conservative since most aviators would have been reluctant to admit refusing or rushing missions, even in a confidential survey.

Although Sliosberg (1962) and Delahaye and Auffret (1982) reported pilots did not experience initial onset of back symptoms until they exceeded 300 hours of flight time, a significant number of U.S. Army aviators reported the onset of symptoms within their first few hours of flight (Figure 4). Indeed, 50.1 percent of those who reported symptoms said that their symptoms appeared at less than 300 hours. The reason for this discrepancy is not clear, but probably relates to differences in the populations studied. This survey studied a considerably larger number of individuals and did not confine itself to any specific group of aviators. Pilots were sampled at different levels of experience, including student pilots, and in many different types of units. No other previous study we know of has surveyed such a diversity of pilots.

One of this survey's more interesting aspects was the finding that the pain reported by the pain group was very transient, lasting less than 24 hours for more than two-thirds of the group (Figure 5). For most pilots, episodes of back pain were induced only by flying helicopters, and the symptoms tended to begin resolving rapidly after ending a flight. Clearly, for these individuals, there is something very specific to the helicopter flying environment that induces their symptoms. Historically, the two factors most widely implicated in the etiology of helicopter back pain have been vibration and the poor ergonomic design of most helicopter cockpits (Delahaye, 1982; Fitzgerald, 1968; Fitzgerald, 1972; Gearhart, 1978; Rance, 1974; Shanahan, 1984a; Shanahan, 1984b; Sliosberg, 1962).

It is well documented in the aeromedical literature that most helicopters subject their occupants to vibration that coincides with the resonant frequency of the human spinal system (Delahaye, 1982; Gearhart, 1978; Shanahan, 1984b; Wilder, 1982). Repeated exposures to such conditions have been speculated to cause microtrauma to the spinal system that eventually leads to back pain. That a large proportion of pilots experience back pain within the first few hours of flying helicopters tends to argue against this theory. Furthermore, work by Shanahan and Reading (1984a) using helicopter cockpit mockups on vibration tables has shown the presence or absence of helicopter-similar vibration had no influence on the time of onset of pain or on pain intensity for subjects exposed to these conditions. Subjects complained of pain during a two-hour "flight" regardless of whether vibration was present or not. In a similar study, Pope and co-workers (personal communication) found that all their subjects reported back pain when exposed to a two-hour "flight" in a helicopter cockpit mockup, and the subjects actually reported less pain when exposed to helicopter-similar vibration than when subjected to the static condition. Furthermore, the subjects used by Pope and co-workers were students who had neither reported previous episodes of back pain nor had they ever flown helicopters. Consequently, it appears that vibration plays a very small role in the etiology of the acute and transient back pain the majority of afflicted aviators in this study reported.

The more likely etiological factor in this syndrome is posture. That posture can be the source of low back pain has been suggested by several researchers. Magora (1972) has shown occupations that force workers to sit for prolonged periods or those that involve almost no sitting had a high incidence of low back pain. Keegan (1953) pointed out that the sitting position without adequate lumbar support and a trunk-thigh angle of less than 105 degrees causes a considerable flattening of the normal lumbar lordosis. This flattening creates stresses which probably cause pain, especially for persons with underlying spinal pathology. Andersson and co-workers (1979, 1977, 1974) have made quantitative measurements of intradiscal pressure in the lumbar spine and the myoelectric activity of back muscles for various postures. They found lumbar intradiscal pressure was highest for unsupported sitting with the spine flexed anteriorly. Likewise, myoelectric activity increased with forward flexion of the spine and asymmetric loading for a constant degree of spinal flexion. They concluded increased myoelectric activity was indicative of localized muscle fatigue (Andersson, 1977).

The ergonomic design of most helicopter cockpits forces the pilot to assume a slumped and asymmetrical posture to operate the controls (Figure 6). This posture must be maintained throughout the flight since full aircraft control requires simultaneous input from all four extremities. Furthermore, most U.S. Army helicopter seats have back angles of less than 105 degrees and provide little or no lumbar support. Consequently, the position pilots assume to fly a helicopter is completely contrary to the ergonomic principles discussed here. The forward flexed, asymmetrical posture most pilots assume causes a flattening of the normal lumbar lordosis and creates high intradiscal pressures and increased myoelectric activity of the paraspinous musculature. Based on these observations, it is not surprising to find a high prevalence of back complaints from helicopter aviators. Although poor posture alone can cause pain, it is important to consider that this postural condition may be aggravated over the long term by the concomitant exposure to vibration that coincides with the resonant frequency of the spinal system. The combination of these factors over time may act synergistically to cause pathological changes in the spinal system. However, to determine the relative effect of these two factors will require further laboratory and epidemiological studies.

Figure 6. Pilot seated at controls of UH-1H helicopter. Note the flexion of the lumbar and thoracic spine as he leans forward to rest his right forearm on his right thigh.

This discussion has confined itself to those aviators who reported relatively transient symptoms that tended to resolve rapidly after terminating flight. Nevertheless, there was a significant number of afflicted aviators who reported much more persistent symptoms. It was shown that the aviator group who experienced symptoms lasting longer than 48 hours tended to have more years on flight status than the transient pain group. Their symptoms also appeared to be more frequent and severe and they reported a much higher incidence of numbness of the legs associated with their pain. In general, the persistent pain group complained of symptomatology that is much more typical of the patients described in most clinical studies of low back pain (Roland, 1983). It is tempting to speculate the transient group represents a group with essentially normal spines that are reacting appropriately to a rather provocative postural stimulus. Consequently, they only experience pain while flying and their symptoms resolve rapidly after ending a flight. It is possible repeated exposure to these conditions leads to pathological changes in the spine that account for the more severe symptoms experienced by the persistent pain group. Unfortunately, this study did not determine whether they initially experienced transient symptoms early in their aviation careers and progressed to their present state after several years exposure to helicopter flight. Nevertheless, it is an intriguing possibility that would be worthy of exploration in future studies. Another possibility is they had some preexisting spinal pathology, either congenital or traumatic, that made them more susceptible to the stimulus of flying helicopters. This theory is supported somewhat since the persistent pain group reported a significantly higher rate of previous back injury than the transient pain group ($p < 0.001$). In either case, this group deserves further identification and evaluation.

In this study, we have demonstrated that back pain in U.S. Army helicopter pilots is extremely widespread and apparently has a significant negative influence on safety and mission accomplishment. Although this affliction has been known and well described in the literature over the last two to three decades, very little has been done to correct it. Much effort has been expended toward reducing vibration in helicopter designs during this time because of its deleterious effects on the airframe and its various mechanical and electrical systems. But, the vibration reduction has had little or no effect on reducing the incidence of back pain in helicopter pilots. In our opinion, a significant reduction in the incidence of back problems in helicopter aircrew members will not be achieved until helicopter seating and control configurations are designed to established ergonomic principles.

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MUSCULO-SKELETAL ILLNESSES AMONG WORKERS EXPOSED TO LOW-INTENSITY WORK LOAD OF LONG DURATION

by

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Summary

Low-level, continuous muscle load of long duration has received increasing attention as a potential source of musculo-skeletal injury. This paper presents evidence which indicate a quantitative relationship between the level of static load on shoulder muscles and the risk of developing musculo-skeletal illnesses in the shoulder and neck. Constrained working postures are probably the most frequent cause of low-level, continuous muscle load, but such loads may also develop for other reasons as illustrated by an example of a probable stress-related development of muscle tension. It is pointed out that aircraft pilots are exposed to a number of factors which can contribute to the development of muscle tension. Low-level muscle tension may therefore be an important health problem for this profession, but this remains to be demonstrated in more specific projects.

Introduction

Work-related back pain is traditionally associated with high peak loads on the spine, such as in the lifting of heavy objects. The intervertebral disk may collapse, or other structures of the spine may be strained in such a way that pain is occurring. For specialized groups such as aircraft pilots vibration with its effect on the spine is another risk factor. A third potential source of back problems is low-level, continuous load of long duration.

Low-level loads have traditionally not been considered a risk factor for back injury, perhaps because the combination of load intensity and duration in the past rarely exceeded a tolerable strain level for most occupations. More recently, constrained working postures and thereby low-level continuous muscle load has received increasing attention as a source of musculo-skeletal injuries (1,2,3,4,5). This may be due to an increasing demand for work efficiency, which for some occupations translate into hours of continuous muscle load. This kind of load may affect muscles in the lumbar region, and thereby contribute to low back pain, but is probably more of a problem for muscles in high back, neck and shoulders.

While it is becoming generally accepted that low-level, continuous muscle load is a considerable problem in many work situations, little is known regarding acceptable levels of load, individual risk factors for the development of such injuries and the underlying pathophysiological processes translating long term load into muscle pain and musculo-skeletal illness.

Methods and material

Work has been in progress for several years at the Institute of Work Physiology, trying to answer some of these queries, and in particular what may be considered an acceptable level of load. Muscle load is measured by surface electromyography. The calibration of the EMG signal relative to muscle force follows largely the procedure of Jonsson (6). Health consequences of such loads are assessed in terms of the rate of recorded sick leaves due to musculo-skeletal illnesses in identified groups of workers. All workers within the same group have similar work situations and thereby, hopefully, similar load on selected muscles.

Medical diagnoses associated with the sick leaves were collected from local health authorities and general practitioners. Musculo-skeletal illnesses like myalgia, tendonitis, low back pain, ischiadis, tendovaginitis etc. were included in the material, whereas illnesses like arthritis which are not considered to be developing as a consequence of muscle load, were excluded from the analysis of possible, work-related musculo-skeletal illnesses.

The common denominator of this class of illnesses is that the patient is suffering from a high level of pain. The recording of a musculo-skeletal sick leave is interpreted to indicate that the patient has experienced an episode of pain of sufficient intensity and duration to visit a doctor. The doctor has then agreed that the patient had this medical condition and was unable to work. This is the underlying basis of the statistical analysis, and the only other information used is the location of the illness on the body. Considerable effort has gone into contacting general practitioners to establish the body location of the injury if this was not clear from the first diagnosis.

It is necessary to accept a certain uncertainty in the classification of the illnesses, but this uncertainty is likely to be small. A few sick leaves may have received a "relevant" diagnosis which is not correct even by the relatively coarse classification used, and the opposite is also possible. In addition, we have been unable to identify diagnoses in the case of about 5% of all sick leaves, making it likely that our data represent a low estimate of the problem, especially since interviews have established that some workers continue to work while experiencing very high levels of pain.

RESULTS

Muscle load due to constrained working postures

Three projects have been carried out where the workers are shown to maintain a steady muscle load throughout the working day. The projects are based on groups of female workers doing electromechanical assembly work, sewing or service work on North Sea oil platforms. In all projects, particular attention was given to load on the trapezius muscles.

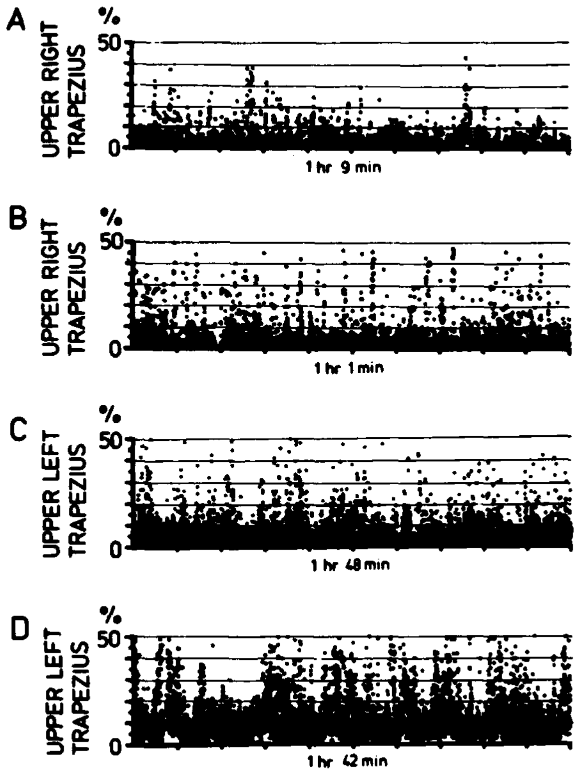

Fig. 1

Muscle load on the trapezius for 4 different female workers cleaning cabins on an oil platform. The trapezius recording with the highest load from either right or left trapezius is shown. Each point in the 4 recordings shows mean load in one second intervals, in percent of maximal voluntary contraction (MVC). Notice the variable length of the recordings, which are shown in full for each worker.

Fig. 1 shows 4 examples of load on the upper trapezius muscle while cleaning cabines on a North Sea oil platform. The data were collected from 4 different female workers. For each worker the recording from either the right or the left trapezius which showed the highest muscle load, was selected. Each point in the 4 recordings represents mean muscle force in an interval of one second, as a percentage of maximal voluntary contraction (MVC). The points are plotted consecutively to show variations in load throughout the recording period, which lasted from 1 hour 1 minute to 1 hour 42 minutes.

In Fig. 1A to 1C points near 0% MVC are present all the time. There are also short periods of relatively high muscle load, near 50% MVC, at irregular intervals throughout the recording period, but median muscle load is very low all the time. Fig. 1D shows a recording where the muscle load remains larger than zero for periods of a few minutes. This is seen as unmarked patches underneath the band of points which indicate the variation in muscle load. The load on the trapezius muscle must be considered intermittent even for this worker, since the periods with low static load are very short. This work situation can therefore be considered to create a low-intensity, intermittent load on the main shoulder muscles. However, continuous monitoring of activity through heart rate and activity log showed that this work pattern might be sustained for several hours without any breaks, for a total of 8 hours throughout the 12 hour working day.

Fig. 2 shows load on the trapezius muscle of 4 sewers. The figure is similar to Fig. 1, except that each worker did two different sewing operations during the recording period. One sewing operations is represented in all 4 recordings, the other operations are all different. The muscle load does not change much when changing to a different sewing operation, except for the example in Fig. 2C where the last operation, using a semi-automatic machine, clearly is less demanding. However, this particular operation only employs one of about 80 sewers at any time.

It is apparent that the band of points which indicate load on the trapezius is shifted away from zero load for all recordings in Fig. 2. The muscles are always working, except in short periods when a set number of garments are finished. The finished

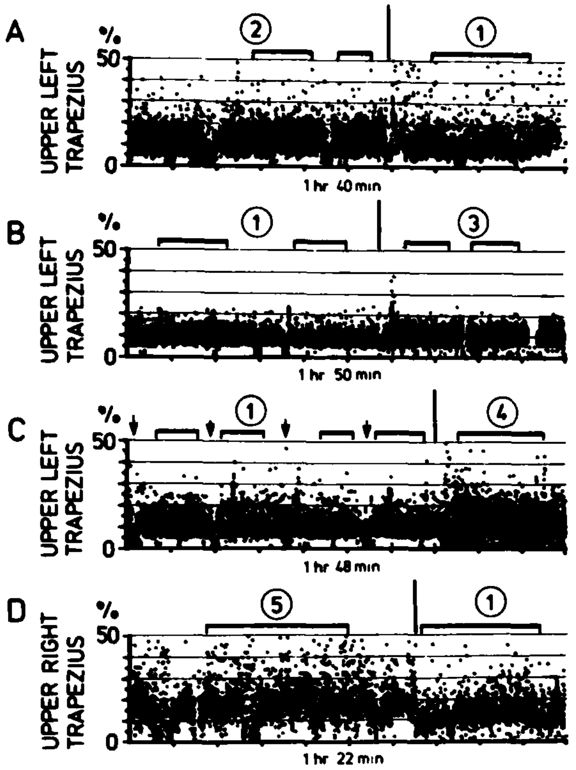

Fig. 2

Muscle load on the trapezius for 4 different female sewers, making thermal clothing. Each worker performs two sewing operations separated by a vertical bar and marked by a number in a circle. The trapezius recording with the highest load is shown. The figure is otherwise similar to Fig. 1.

garments are moved to a store and a new lot prepared for sewing. This part of the work cyclus with long periods of static load on the trapezius, interrupted by short pauses, are particularly noticeable in Fig. 2C where the breaks in muscle load are marked by an arrow. These breaks are obviously important, but the long periods with static load may nevertheless be considered the dominant feature of the work pattern. The quantification of muscle load was therefore based on periods with static work load, as indicated by horizontal bars on top of each panel. The bars show recording periods used in the quantitative analysis.

The results of the quantitative analysis of work load on the trapezius for the service workers on the oil platforms and the sewers are shown in Fig. 3. The figure shows static work load (6) on the trapezius for 9 recordings from 9 different service workers (A), and for 25 recordings of sewing operations by 15 sewers (B). Median static work load on these muscles are 1.1% MVC for the service workers and 5.8% MVC for the sewers. Most sewers work with a static muscle load varying between 3 and 9% MVC. Thus, there is a very clear statistically significant difference in work load on the trapezius between the two groups of female workers.

The work load in a third work siutation, assembling parts to telephone exchanges, has not been analysed quantitatively to the same extent as the above work situations, but inspection of individual recordings has shown that the load pattern on the trapezius for this group of workers is similar to that of the sewers, except that the level of static load is higher. The median static load is likely to be between 8 and 10% MVC.

Thus, these three groups of workers represent work situations with distinctly different work loads on the shoulder muscles. In particular, there is little overlap in load on the trapezius between the groups even when taking the variation within each group into account.

Development of illnesses in the shoulder and neck

To assess the effect of muscle load on the trapezius, used as an indicator of load on the shoulder, the load has to be correlated with musculo-skeletal complaints developing in the same body region. Also, it is necessary to take into account the varying time of employment of the different workers. This because time of employment in the work situation of interest is also time of exposure to the work load, and increasing length of exposure to load is likely to increase the chance of contracting a load-related illness.

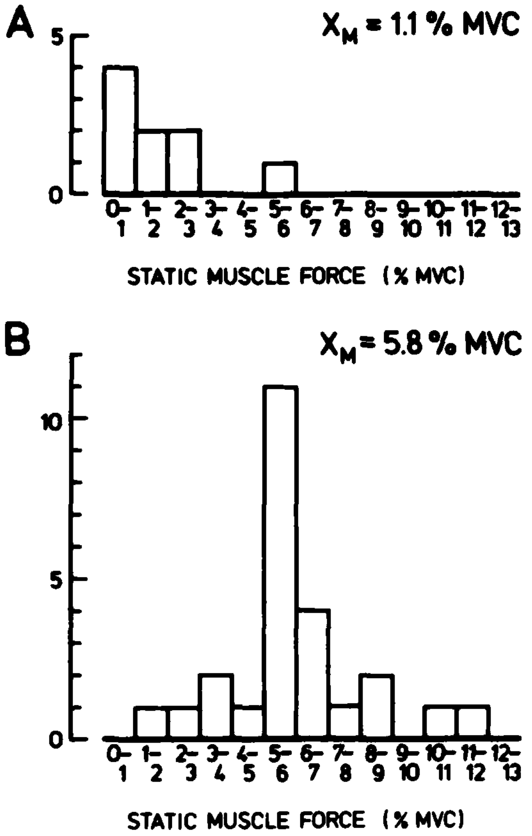

Fig. 3

Quantitative analysis of static load on the trapezius for the two groups of workers illustrated in Figs. 1 and 2. A. Female cabin cleaners. B. Female sewers. 25 work operations by 15 sewers are included in the histogram.

Fig. 4 shows the fraction of workers with sick leave due to musculo-skeletal illnesses in the shoulder or neck as a function of time of employment for the 3 experimental groups with a relatively stable load throughout the working day (the service workers on the oil platforms, the sewers and the workers doing electromechanical assembly work). In addition, similar data for a control group with varied office work is shown, except that the data available for this group do not allow any differentiation of musculo-skeletal sick leaves into different body locations. All musculo-skeletal illnesses including low back and lower arm injuries are therefore included in the data for the control group. Each of the points for the experimental groups in Fig. 4 is based on at least 20 persons, varying from 22 to 160. The control group is much smaller, and the data for this group is based on groups of 9 to 19 persons.

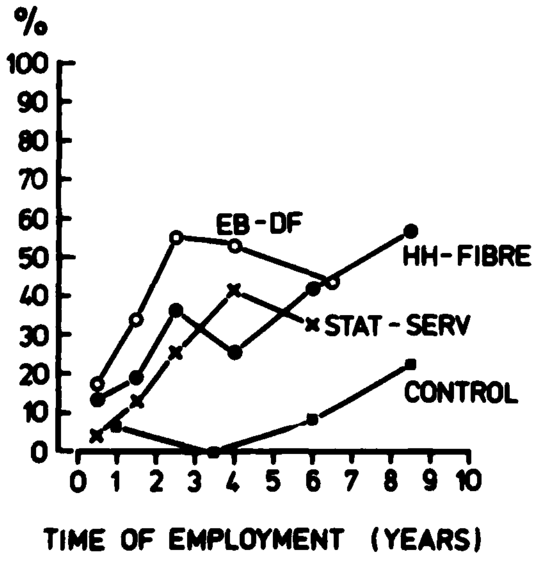

Fig. 4

Percentage of workers with one or several sick leaves due to musculo-skeletal illness located to the shoulder and neck, as a function of time of employment. Workers from 3 different work situations with high static load (EB-DF), moderate static load (HH-FIBER) and dynamic load (STAT-SERV) on the trapezius muscles is shown. A control group with varied office work is also included.

For each of the experimental groups there is a clear tendency for an increasing fraction of workers to develop musculo-skeletal illnesses located to the shoulder and neck within a few years after employment. This is in marked contrast to the control group where only one of 35 females record such illnesses the first 5 years of work, and only 3 of 21 with 5 to 10 years job experience. The difference is statistically significant, even with the small number of people in the control group and despite the inclusion of all musculo-skeletal illnesses, regardless of body location, in the control group.

When comparing the experimental groups, the fraction of workers with a musculo-skeletal sick leave due to an injury in the shoulder and neck increases from 4 to 25% the first 3 years of employment for female workers with the most dynamic load, from 13 to 36% for the female workers with the moderate static load, and from 18 to 55% for the female workers with a high static load. These results indicate a continuous, graded risk of developing musculo-skeletal illnesses with an increasing level of static load on these muscles. The differentiation between the three groups are less clear for workers employed more than three years. For two of the groups there is a reduction in the fraction of workers with recorded musculo-skeletal illnesses in the shoulders and neck among workers with the longest time of employment. This may in part be due to a selection process where workers who suffer long periods of pain at work try to find alternative employment, leaving those who are able to meet the physiological demands of the work situation without too much discomfort. The two groups of workers where this effect is most noticeable also showed the highest over-all incidence of musculo-skeletal illnesses. (The service workers had a very high rate of injuries in the low back and the lower arms in addition to shoulder and neck.)

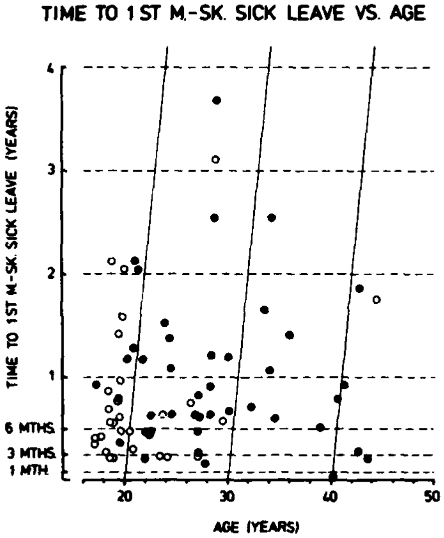

Fig. 5

Time from start of employment to first musculo-skeletal sick leave as a function of age for workers doing electromechanical assembly work. Each worker with a recorded musculo-skeletal sick leave is represented with a circle in the plot, open circle if employed full time or filled circle if employed part time. The occurrence of subsequent musculo-skeletal sick leaves, if any, is not shown.

Fig. 4 does not contain specific information regarding time of occurrence of the musculo-skeletal sick leaves, this (or these) may occur at any time during the time of employment for each individual. Fig. 5 shows time of occurrence after employment of the first musculo-skeletal sick leave for each individual with such sick leaves, as a function of age. These data are from the female workers doing electromechanical assembly work with a high static load. It is evident that it takes very little time from start of work until the first musculo-skeletal sick leave occurs, commonly 3 to 9 months for full time workers and a few months longer for part time workers. Young females appear to be particularly at risk, and there are indications of older people being able to sustain the load for somewhat longer time periods.

Even though these sick leaves occur soon after employment, they are far from trivial incidents. The duration of musculo-skeletal sick leaves among the same group of workers is shown in Fig. 6 for full time and part time workers. Median duration is about 5 weeks, and the duration is usually at least 3 weeks. Some may last for half a year or longer, and cases receiving permanent disability allowances are known to occur even among very young people. The figure also shows that the complaint in most cases was located to the shoulder and neck, but also with a significant number of sick leaves due to low back disorders.

Figs 5 and 6 present data from one of the projects, but near identical results regarding the timing and duration of musculo-skeletal sick leaves are also found for the other groups of workers, despite the considerable variation in load on the trapezius muscle between the different groups. Thus, it appears to be a general result that the first period of work is particularly dangerous with regard to the development of musculo-skeletal injuries, if the work duties demand a sustained muscle load. A reduction in total hours of work and an age of 30 or older when starting work appears

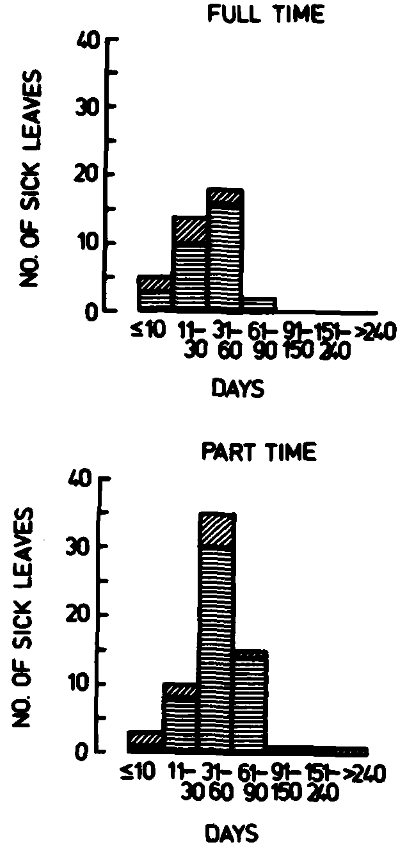

Fig. 6

Duration of musculo-skeletal sick leaves for workers employed full time (top) and part time (bottom). Horizontal hatching indicates sick leaves located to high back, shoulder and neck, diagonal hatching low back complaints.

to delay the onset of such illnesses. The latter effect could be explained by a certain amount of muscle training among the older workers, possibly provided by previous, similar job.

Muscle load due to stress

The above projects are all based on groups of workers with a work situation which specifies a continuous muscle load due to the need to adapt a specific posture. Postural load of muscle is most readily understood and is also the easiest way of ensuring a relatively invariant load among subjects in similar work situations. However, muscle may be activated by other mechanisms, and muscle tension is a well-known reaction to stress. Recent experiments in our laboratory illustrate this point. Fig. 7 shows simultaneous recordings from four separate muscles in both shoulders (trapezius), high back (rhomboid) and the lumbar region of the back, from one subject who had to perform a complex VDU-based choice-reaction time test followed by a dynamic heterophoria eye measurement. The tests were performed with a well-balanced, sitting posture which should minimize postural strain. The first test demanded a high level of reasoning, while the other would strain the external eye muscles. The figure presents EMG data in a similar way to Figs. 1 and 2, and it is evident that the person developed a static muscle tension of about 2% of maximal voluntary force both in upper right trapezius and right rhomboid. There is a similar pattern of tension in the other two muscles, with a higher load in the low back muscles and less in the upper left trapezius. The static tension disappears during a pause betwen the two tests, and there are also short periods of a few seconds with reduced tension during the test. The similar pattern of tension in all four muscles is a striking feature of this experiment, and makes it unlikely that variation in load is due to specific body movements. Nor were such movements evident when the subject was observed during the experiment. It may therefore tentatively be assumed that the recorded tension represents an unconscious muscle reaction to a task requiring a high level of concentration, but with no need for body movements. The level of muscle tension for this individual must be considered potentially harmful if tension is maintained for long periods of time, judged by the previous results.

Similar experiments on other subjects gave qualitatively similar results, but with considerable variation in the absolute level, as well as in the temporal pattern of muscle tension. In contrast to this interpersonal variation there were a strong tendency for the same person to develop similar temporal patterns of tension in different muscles. These preliminary findings are now being explored in new, more controlled experiments.

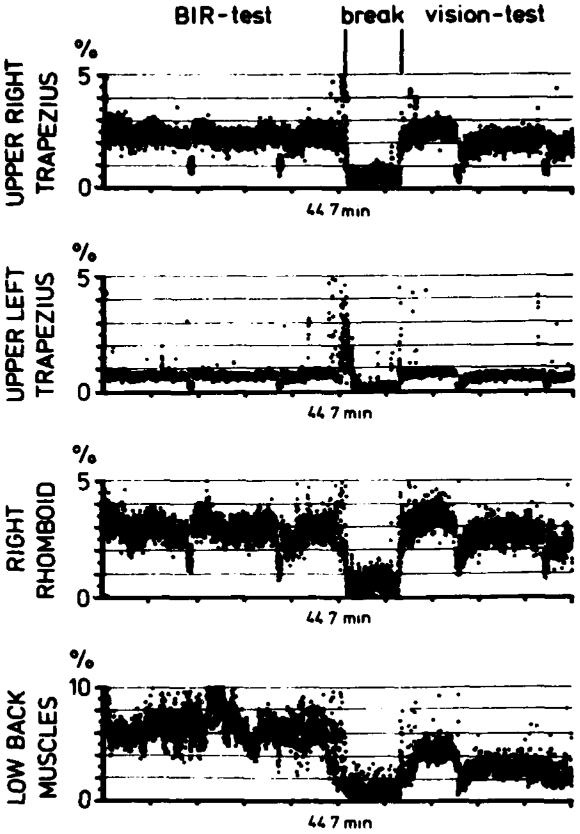

Fig. 7

Simultaneous recordings of muscle load in 4 muscles when performing a VDU-based choice-reaction time test (BIR-test) followed, after a break, by a dynamic heterophoria eye measurement. Each point in the four graphs represent mean muscle load in 0.5 second intervals, as a percentage of maximal voluntary force.

DISCUSSION

A major point emerging from the results is that even a low-level, intermittent load can provide a risk for developing musculo-skeletal illnesses if the load has to be maintained for long enough time. Also, the indication of a graded risk in developing musculo-skeletal illness with increasing level of static muscle load and increasing time of exposure to the load is interesting. In one of the projects 50% of the workers exposed to high static load and with more than two years employment recorded one or several sick leaves due to musculo-skeletal injuries located to the shoulder and neck. In contrast, few sick leaves of this kind were recorded among the control group with varied office work.

These results are based on measurements of load on the trapezius, and the tolerance for prolonged loads may vary between different muscle groups. In particular, muscles developed to counteract gravity forces have a different muscle fibre composition and therefore higher resistance to prolonged load. Nevertheless, results based on the trapezius muscle may serve as an indication of tolerance to load for muscles in general, until more specific evidence regarding such effects on other muscles and other body structures is available. It is also appropriate to point out that there is at present little knowledge regarding the effect of muscle training in reducing the risk of contracting a musculo-skeletal illness. Nor is the effectiveness of various kinds of muscle training known. Muscle load during work as illustrated in Figs. 1 and 2 is primarily due to constrained working postures or a demand for continuous movement of limbs. It is less evident that muscle load also may be generated by a demand for concentration or by a state of general tension as indicated in Fig. 7. The subjects participating in these experiments usually found the tests extremely tiring, and it is an impression that the level of discomfort is highest among those generating a high level of muscle tension during the test. However, it is premature to relate discomfort exclusively to the level of static load since many other physiological and hormonal reactions may take place simultaneously.

A potential source of muscle activation which to our knowledge is not yet tested in occupational experiments, is vibration. Vibration would be expected to activate sensory organs in the muscles. These would then provide a facillatory input to the motoneurones in the spinal cord, and thereby cause muscle contraction. Whether this introduces a significant increase in the level of muscle tension beyond that due to other activation mechanisms remains to be demonstrated.

Finally, it is appropriate to point out that aircraft pilots and crew are potentially exposed to all the activation mechanisms for muscle tension mentioned in this paper: constrained posture, continuous movement of limbs, demand for a high level of concentration,exposed to vibration and possibly a high level of general tension. Thus, such personnel (or subgroups of such personnel) may develop very high levels of muscle tension, contributing to considerable feelings of discomfort during active service.

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DISCUSSION

BOWDEN, CA: Do you know of any group of workers exposed to constrained postures in which the low back rather than the upper back is the principal source of pain or the principal area in which pain is felt?

WESTGAARD, NO: I think it's true that, in general, the upper muscles would be the group of muscles most at risk. Having said that, we have seen groups of workers forced to adopt a forward-bending posture without having any real lifting task to perform. In this group, there was a predominance of pain reported in the lumbar region. So, it does occur; and, in fact, whenever it seems possible to identify the part of the body being strained, then the pain appears to be in that particular part. We have also found groups reporting pain in the lower arms when they have had to perform repetitive motions.

BOWDEN, CA: I will comment that such a group, if it was not a group of drivers or pilots, would be of great interest because this group would not be exposed to vibration and yet be exposed to the postural constraints similar to those of drivers. What group is this?

WESTGAARD, NO: It is a group which we are working with, and of which data are not yet published.

TROUP, UK: We have heard today, and there may be more papers to come, of retrospective epidemiological surveys. Now these are useful in identifying one or two key areas, but if you are going to learn anything, you have to set up a prospective epidemiological study. I regard an epidemiological study as, perhaps, simply validating the need for doing the job properly. Then you must set up a pilot trial; make sure that your methods are satisfactory; and that any measurements you make are repeatable. Then you go on and do the prospective epidemiological study, with all the variables that you think are required and which you can afford to include. It's not simple. If I could just add, I'm not at all happy, for example, that Dr. Bowden suggested that some of the population, subject to postural stress without vibration, could be used as control subjects for vibration. To me, this is simply not done. You have to have a true control. You may have to use the factorial method of analysis, but the control populations have to be doing comparable physical exertions; they have to be struggling with comparable controls, comparable external forces, and so forth. I think we have to be very careful about what we mean by an epidemiological control, because the rules of epidemiology are very strict.

ANALYSE BIBLIOGRAPHIQUE
DES CARACTERISTIQUES BIOMECANIQUES
DE LA COLONNE VERTEBRALE

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RESUME :

Pour améliorer les modèles dynamiques de la colonne vertébrale, il est non seulement indispensable d'appliquer aux différents coefficients,de raideur, d'amortissement, et de masse les valeurs les plus exactes possibles, mais il est également indispensable de connaître le comportement mécanique des différents matéraux (ici biologiques) constitutifs de la structure.

Après un rappel schématique de l'anatomie de l'unité vertébrale, l'auteur fait l'analyse bibliographique des caractéristiques mécaniques, du disque, des ligaments et des corps vertébraux. C'est ainsi que sont rapportées les valeurs, maintenant communément admises, de fluage, de relaxation, de pression intranucléaire , obtenues lors d'essais conduits en flexion, extension, inflexion latérale, torsion et cisaillement du disque. Les études intéressant la valeur de ces paramètres pour les ligaments sont également faites. L'auteur énonce les données obtenues sur la propagation des ondes vibratoires dans la colonne et donne un exemple d'étude cinématique.

INTRODUCTION

La biomécanique vertébrale est de plus en plus étudiée à l'aide de modèles en raison du développement de l'informatique qui rend possible l'utilisation des techniques d'analyse numérique de plus en plus puissantes. Quels que soient leurs modes de présentation la structure de ces modèles est univoque,bâtis qu'ils sont à l'aide de l'outil mathématique. C'est ainsi qu'il s'agit le plus souvent de chercher la solution d'un système d'équations différentielles, linéaires ou non, à coefficients constants ou non, définies dans un domaine connu. Mais la théorie physique des modèles est souvent pervertie quand elle est appliquée aux sciences biologiques. La division du domaine de définition en deux plages distinctes - correspondant à des niveaux d'excitation d'abord humainement admissibles, puis inadmissibles- détermine en pratique de biomécanique "in vivo" deux types de modèles ; le modèle de comportement et le modèle de prédiction. Le modèle de comportement défini le plus exactement possible, la dynamique vertébrale quand la structure est soumise à des amplitudes de déplacement ou de force supportables par un sujet. Les résultats des calculs sont confrontés aux données expérimentales. Le modèle de comportement qui n'a pas d'intérêt au plan de la connaissance possède, par contre, une valeur spéculative. Précis dans un certain domaine on infère qu'il le sera également dans la plage supérieure d'excitation, celle ou l'expérimentateur n'a pas accès car l'application d'une force ou d'un déplacement de grande amplitude ne manqueraient pas de provoquer des lésions graves de la colonne vertébrale du sujet qui y serait soumis. Conceptuellement, de comportemental le modèle est devenu prédictif. Son intérêt est double pour le biomécanicien, puisqu'il se conduit -hypothétiquement- comme un modèle de connaissance et qu'en retour il permet, par exemple, de spéculer sur l'efficacité de tel ou tel type de protection. L'expérimentateur devient expérimentaliste.

Il est donc clair qu'un modèle prédictif est - ou risque d'être - d'autant plus utile que le modèle de comportement est exact. Les résultats délivrés par ce dernier sont d'autant plus proches de la réalité que les valeurs des coefficients des paramètres dont il étudie les variations sont précises.

Ce sont les valeurs de ces différents coefficients qui sont rapportés dans une analyse bibliographique concernant les éléments d'une unité vertébrale ; les corps vertébraux, les disques, les ligaments. Dans une première partie l'analyse fait le point sur les valeurs de fluage, de relaxation, de pression, etc... pour des études conduites en flexion extension, inflexion latérale, torsion et cisaillement. Dans un second paragraphe l'analyse rapporte très brièvement les données actuellement collectées concernant la propagation des ondes vibratoires dans la colonne. Un troisième chapitre énonce une méthode d'étude de la cinématique des unités vertébrales.

Auparavant, rappellons très schématiquement l'anatomie d'une unité vertébrale.

2) RAPPELS D'ANATOMIE DE LA COLONNE VERTEBRALE

La colonne vertébrale des mammifères est un ensemble ostéoligamentaire doué de mobilité. Dans l'embranchement des céphalocordés elle n'est représentée que par une corde, formation d'origine endodermique qui s'isole précocement de la région de l'hypoblaste. C'est une baguette allongée, de consistance cartilagineuse qui s'étend d'une extrémité à l'autre du corps. Dans leurs déplacements, les céphalocordés se meuvent par ondulation latérale et l'élasticité passive de la corde est antagoniste des flexions provoquées par les muscles - DRACH 1948 (9).

La corde se retrouve dans tous les stades embryonnaires des vertébrés avec les caractères qu'elle présente chez les céphalocordés, BRIEN, DALCQ 1954 (4). Avec la formation d'un squelette axial, la corde dégénère plus ou moins et peut même disparaître. Si c'est le cas chez les oiseaux, chez les mammifères elle se conserve sous forme d'un reliquat embryonnaire au niveau des disques intervertébraux ou elle édifie le nucléus pulposus. DEVILLERS 1954 (6). Chez quelques reptiles, se différencie, à l'intérieur de la corde, du cartilage, qui s'ajoute au corps vertébral.

La colonne vertébrale proprement dite est réalisée par l'empilement des vertèbres. Elle présente quatre courbures antéro-postérieures chez l'homme :

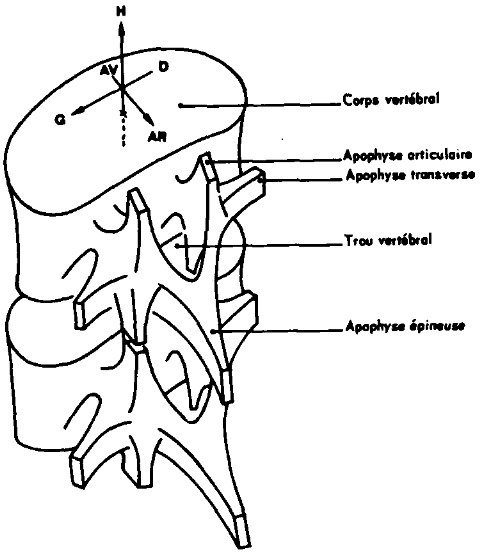
- cervicale : convexe en avant,
- dorsale : convexe en arrière,
- lombaire : convexe en avant,
- sacrée : convexe en arrière.

Il existe sept vertèbres cervicales, douze dorsales, cinq lombaires, cinq sacrées (soudées), une ou deux coxygiennes.

2.1 - OSTEOLOGIE

Toutes les vertèbres, quelle que soit la région à laquelle elles appartiennent sont morphologiquement équivalentes et constituées sur un même type. TESTUT, LATARJET 1928 (47), TESTUT L., JACOB O., 1929 (48). Schématiquement (figure 1), chacune d'elle présente :

- *un corps situé en avant* : il s'agit d'une masse osseuse hétérogène, constituée d'os spongieux enfermé dans une coque d'os compact,
- un trou vertébral situé en arrière du corps,
- une apophyse épineuse,
- deux massifs osseux latéraux constitués de trois apophyses : deux articulaires (inférieure et supérieure), une transverse, les pédicules et les lames unissent les massifs osseux latéraux respectivement au corps en avant et à l'épineuse en arrière.



SCHEMA D'UN SEGMENT VERTEBRAL.

Figure 1

2.2 - ARTICULATIONS VERTEBRALES

Les vertèbres sont reliées entre elles par des articulations au niveau des corps et des apophyses articulaires.

Un disque intervertébral réuni les vertèbres deux à deux.

Sa hauteur chez l'homme varie de 3 mm dans la région cervicale à 9 mm dans la région lombaire. Le disque est constitué d'un anneau fibreux périphérique et d'une substance gélatineuse centrale, reliquat de la corde embryonnaire. Les disques intervertébraux sont très résistants et dans les mouvements exagérés de la colonne vertébrale ils ont plus tendance à arracher les surfaces osseuses sur lesquelles ils s'insèrent plutôt que de se rompre. Alors que les disques intervertébraux réalisent une synarthrodie, les articulations des apophyses articulaires sont de type classique avec capsule et synoviale (diarthrose).

Les vertèbres sont en outre réunies à distance par des ligaments au niveau des bords des apophyses transverses et épineuses. Seuls les pédicules ne sont pas reliés entre eux. L'espace laissé vacant réalise le trou de conjugaison, voie de passage des nerfs rachidiens.

2.3 - FORMATIONS LIGAMENTAIRES

Ligaments communs

Ce sont des ligaments qui unissent toutes les vertèbres sur la totalité de l'axe osseux. Ils peuvent cependant prendre une importance plus ou moins grande selon leur localisation.

- Le ligament vertébral commun antérieur est situé sur la face antérieure de la colonne.
- Le ligament vertébral commun postérieur est en plein canal rachidien. Il est placé immédiatement devant la moelle épinière.
- Le ligament surépineux : situé en arrière, il unit les extrémités des apophyses épineuses. Il trouve son plus grand développement au niveau cervical.

Ligaments intervertébraux

Les apophyses transverses sont réunies à leur homologues supérieures et inférieures par les ligaments intertransversaires. Le ligament interépineux réunit les apophyses du même nom. Les lames vertébrales sont réunies entre elles par "le ligament jaune". Large, épais, il complète en arrière la fermeture du canal rachidien en comblant l'hiatus qui sépare les lames vertébrales entre elles.

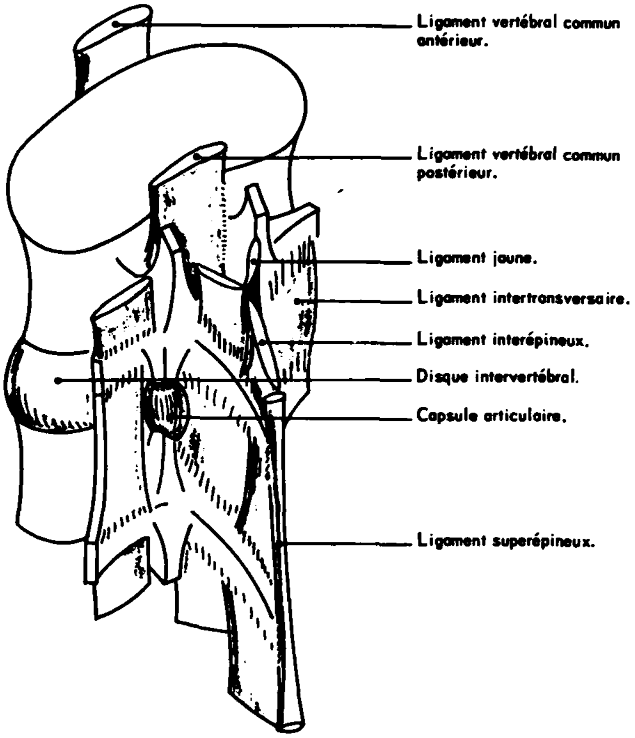
2.4 - LES MUSCLES PARAVERTEBRAUX

Sur la colonne osseuse s'insèrent les muscles paravertébraux. Leur contraction constante permet à l'être humain et plus généralement aux primates de conserver une position verticale. La stabilité intrinsèque de la colonne vertébrale est apportée par les disques intervertébraux et les ligaments. La stabilité extrinsèque par les muscles - MORRIS 1973 (24). La disparition du fonctionnement normal des haubans musculaires telle qu'elle est réalisée dans la myopathie de DUCHENNE montre assez combien la stabilité propre de l'ensemble ostéo-ligamentaire est insuffisante à la conservation de la verticalité WILKINS, GIBSON 1976 (51).

Le schéma représenté sur la figure 3 indique la position et les rapports des muscles qui sont décrits ici, dans la région lombaire.

D'un point de vue purement descriptif et non fonctionnel, la région lombaire est délimitée par un quadrilatère réalisé :

- en haut : par la base du grill costal,
- en bas : par une ligne passant par les crêtes iliaques et le bord supérieur de la première vertèbre sacrée,
- latéralement : par une ligne qui répond au bord externe des muscles spinaux.



LIGAMENTS VERTEBRAUX - DISQUE INTERVETEBRAL.
(Schéma)

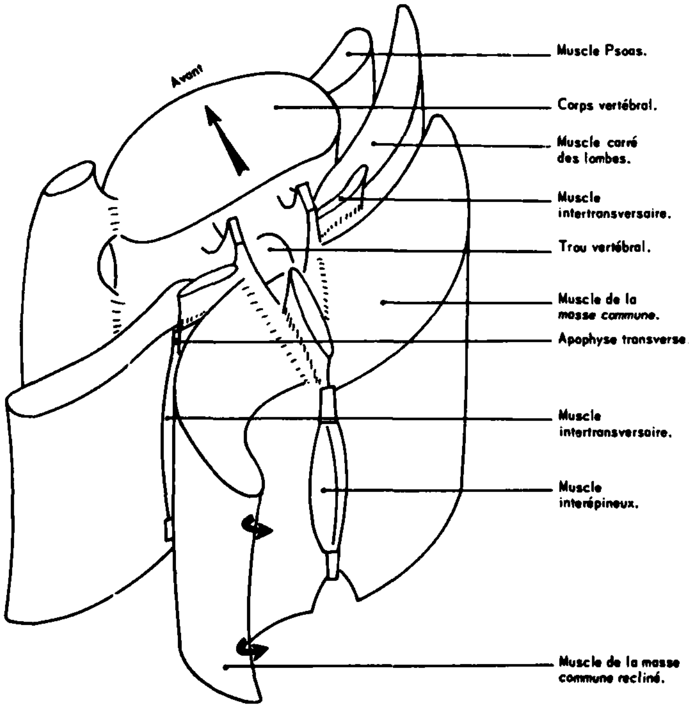
Figure 2

En fait, les vertèbres lombaires constituent les points d'insertion de nombreux muscles qui n'appartiennent pas totalement à la région lombaire (muscles larges de l'abdomen par exemple). Les gouttières larges et profondes qui occupent tout l'espace entre les apophyses transverses et épineuses sont comblées par trois formations musculaires importantes affectant comme elles une direction longitudinale sur toute l'étendue de la région.

- Le muscle sacrolombaire,
- le muscle long dorsal,
- le muscle transversaire épineux.

En réalité ces muscles sont réunis en une masse unique, en partie charnue, en partie tendineuse appelée masse commune.

Action : envisagés isolément, ces muscles spinaux ont les actions suivantes : le sacro-lombaire (ou ilio-costal) est extenseur et fléchisseur de la colonne. Le long dorsal par ses faisceaux externes a la même action, mais l'inclinaison latérale est moins prononcée. Le transversaire épineux est le rotateur le plus puissant. Il porte la face antérieure du côté opposé à la contraction.



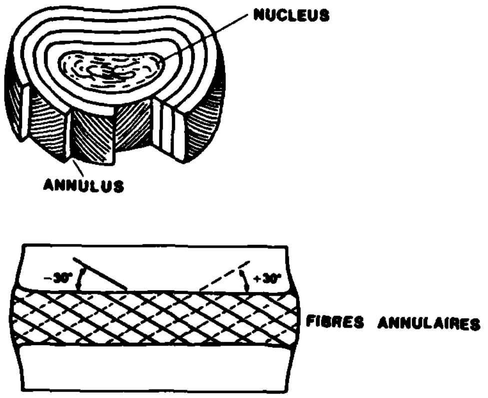
SCHEMA D'UNE UNITE VERTEBRALE FONCTIONNELLE.

Figure 3

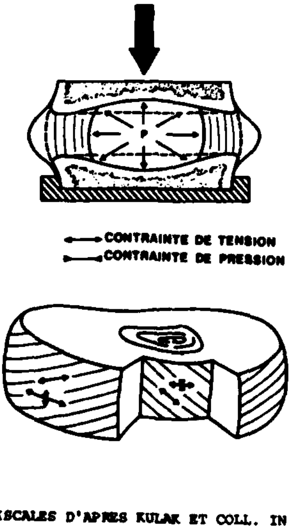
. En avant de la masse commune se placent les muscles intertransversaires des lombes. Ils inclinent de leur côté la colonne vertébrale. Quand ils se contractent à la fois à droite et à gauche, ils fixent solidement chaque vertèbre à celle qui l'encadre. Ils tendent ainsi à transformer la colonne mobile en une structure rigide.

. En arrière de la masse commune s'insèrent les muscles interépineux. Il rapprochent les apophyses sur lesquelles ils sont fixés. Ils sont extenseurs de la colonne.
En avant des muscles de la gouttière vertébrale se placent deux muscles importants : le carré des lombes, le psoas iliaque.
Le carré des lombes situé sur les côtés de la colonne lombaire est tendu de la douzième côte à la crête iliaque. Son action est différente selon l'endroit ou il prend son point fixe. Si le point fixe est sur le bassin il incline de son côté la colonne lombaire par ses faisceaux ilio-transversaires. S'il prend au contraire son point fixe sur le thorax comme cela arrive quelquefois dans le décubitus dorsal, il incline le bassin de son côté.
La portion psoïque du muscle psoas iliaque est tendue de la colonne lombaire au fémur. Elle présente une arcade médio-vertébrale et ne s'insère que sur les bords inférieurs et supérieurs des portions toutes latérales des corps vertébraux ainsi que sur la partie latérale des disques intervertébraux lombaires.
Action : le muscle psoas fléchit la cuisse sur le bassin. Dans la station verticale il prend son point d'insertion fixe sur le fémur. Agissant alors sur la colonne vertébrale il la fléchit en avant. S'il se contracte d'un côté seulement il fléchit encore le tronc mais en même temps il l'incline de son côté et lui imprime un mouvement de rotation. Dans la station debout le psoas combine son action à celle des abdominaux et des extenseurs vertébraux pour assurer l'équilibre du tronc sur les hanches. C'est un muscle important de la statique du tronc.
Outre les muscles de la masse commune du carré des lombes et du psoas qui ont une action véritablement active sur la colonne osseuse, les muscles larges de l'abdomen ont une action passive. Leur activité (fléchisseurs ou rotateurs du tronc) est importante car durant l'action de soulèvement ils diminuent la charge sur les disques intervertébraux en transformant l'abdomen en cylindre à paroi semi-rigide, MORRIS 1973 (24).

3 - BIOMECANIQUE VERTEBRALE : STATIQUE



DISPOSITION DES FIBRES ANNULAIRES D'APRES KAZARIAN
IN "CLINICAL BIOMECHANICS OF THE SPINE" WHITE ET PANJABI



CONTRAINTES INTRADISCALES D'APRES KULAK ET COLL. IN CLINICAL BIOMECHANICS OF THE SPINE WHITE ET PANJABI, 1978

Figure 4

La première réaction du corps humain soumis aux forces mécaniques est une réaction mécanique : une contrainte ou une déformation. Après un certain temps d'excitation mécanique surviennent toute une série d'ajustements comportementaux. L'étude de la biomécanique vertébrale est une première approche de la compréhension des conséquences osseuses ou ligamentaires de ces stimulations en relation avec leur amplitude.

3.1 - LE DISQUE INTERVERTEBRAL

3.1.1 - Anatomie fonctionnelle

Le disque intervertébral est constitué :
- d'un anneau fibreux (annulus fibrosus),
- d'un noyau pulpeux (nucleus pulposus),
- de deux plateaux cartilagineux.

De façon très imagée, on peut comparer cet ensemble à une boîte de conserve cylindrique dont l'anneau forme le corps, les plateaux cartilagineux les couvercles et le noyau le contenu.

- L'annulus fibrosus

L'anneau fibreux constitué de couches tissulaires de fibrocartilage présente une organisation lamellaire identique à celle d'un bulbe d'oignon dans lequel les lamelles seraient extrêmement adhérentes les unes aux autres. Chaque couche unitaire fermée en un anneau tubulaire est fortement insérée sur les deux vertèbres adjacentes.

Cependant les fibres conjonctives constitutives de chaque lamelle sont très obliques par rapport à l'axe vertical. Elles forment un angle de trente degrés sur la direction horizontale. Cette orientation crée une élasticité en traction-compression car l'obliquité des fibres s'inverse d'une couche à l'autre - MARKOLF, MORRIS 1974 (23). L'épaisseur des portions antérieures et latérales de l'anneau est approximativement le double de celle de la partie postérieure juxtamédullaire. Dans cette zone les couches de tissu fibreux sont moins épaisses et la direction des fibres moins oblique. Elle tend à devenir axiale. L'adhérence entre les couches est également moins forte. "Ces facteurs contribuent sans nul doute à créer des conditions favorables à la survenue de hernies discales" MORRIS 1973 (24).

En raison de l'orientation préférentielle des fibres, l'anneau fibreux est anisotrope et non homogène. (Le coefficient d'élasticité varie en fonction, de la distance qui sépare le centre du disque de la périphérie, de l'orientation relative des fibres et de la charge appliquée). Il n'existe pas de passage net entre les fibres des lamelles centrales et la structure du noyau.

- Le nucleus pulposus

Le nucleus pulposus est une substance gélatiniforme et hydrophile dont la teneur en eau est d'environ 88 %. La composition du noyau se modifie avec l'âge ; les substances mucoïdes qui le composent sont progressivement remplacées par du fibrocartilage moins gélatineux. En raison même de la structure de l'anneau fibreux le nucleus est légèrement décentré vers l'arrière. Il occupe 50 à 60 % de la surface totale du disque. Il est constitué de cellules chondrocytiformes dispersées dans une matière intercellulaire ou l'on trouve un maillage de fibres collagènes peu différenciées. Chacune de ces fibres est couverte par un complexe protéo-polysaccaridique. Ce polysaccaride (chondroïtine sulfate) donne au noyau sa grande capacité de liaison avec les molécules d'eau. Mais en fonction de l'âge, la dégénérescence de cet organe s'accompagne d'une diminution de sa teneur en eau. Le noyau peut être considéré comme une substance isotrope et homogène par suite de l'orientation aléatoire des fibres. Il se comporte comme un fluide incompressible, confiné dans un volume constant, en état de contrainte hydrostatique.

- Les plateaux cartilagineux

Composés de cartilage hyalin, ils isolent les deux autres composants discaux (anneau, noyau) du corps vertébral. Le coefficient d'élasticité est à peu près le tiers de celui de l'os spongieux du corps vertébral.

3.1.2 - Propriétés physiques du disque intervertébral

- Fluage relaxation

Le disque intervertébral se comporte comme un matériau viscoélastique. L'application d'une force constante sur la structure fait apparaître un phénomène de fluage. La déformation n'est pas seulement une fonction de la charge, c'est aussi une fonction du temps. HIRSCH et NACHEMSON 1954 (13) n'obtiennent pas de déformation stable du disque par l'application d'une force de 100 daN pendant plusieurs heures (la déformation maximale obtenue est de 1,07 mm).

Le fluage est étudié par MARKOLF et MORRIS 1974 (23) . Les observations sont obtenues sur des pièces anatomiques soumises à quatre charges différentes pendant 70 minutes : les forces les plus importantes provoquent les déformations les plus grandes (à l'asymptote), avec des vitesses de déformations les plus rapides. Corollairement,les plus grandes vitesses de relaxation sont en rapport avec la cessation d'application des charges les plus fortes.

Le fluage est un mécanisme par lequel le disque subit un processus de répartition du stress jusqu'à ce qu'il s'adapte ou qu'il atteigne un état stationnaire par rapport à une charge spécifique. La question qui se pose est de savoir par quel mécanisme se produit ce fluage. "Y a-t-il échange de liquide par les plateaux cartilagineux ? Y-a-t-il une répartition du liquide dans les parois de l'anneau ? Y a-t-il une simple déformation de structure sans aucun échange de liquide ? L'étude de la littérature de ces données montre que les mécanismes responsables du fluage restent obscurs" KAZARIAN 1975 (19).

La plupart des auteurs se sont attachés à déterminer les valeurs des paramètres physiques des structures discales en travaillant le plus souvent sur des pièces anatomiques fraîches. Bien entendu, il n'a jamais échappé à la sagacité des expérimentateurs que les résultats obtenus dans de telles conditions ne sont qu'un reflet plus ou moins éloigné de la réalité puisque les tissus morts ne présentent plus les mêmes caractéristiques d'hydratation, de température, de souplesse, etc... que ceux des tissus vivants.

- Hystérésis

Tous les matériaux viscoélastiques ont des propriétés d'hystérésis qui rendent compte de l'énergie perdue dans la structure soumise à des cycles répétitifs de compression et de décompression. WHITE et PANJABI 1978 (50), dans leur ouvrage "Biomechanism of the spine" rapportent les expériences de VIRGIN réalisées en 1951. L'hystérésis varie en fonction de la force appliquée, de l'âge et de la localisation du disque. Plus la force appliquée est importante plus la courbe d'hystérésis est globuleuse. L'énergie dissipée dans le disque diminue avec l'âge. Elle est plus faible pour les segments lombaires supérieurs que pour les segments inférieurs. L'hystérésis diminue si le même disque est soumis une seconde fois à la même excitation. Ainsi, la dissipation d'énergie dans les disques, qui est un phénomène de protection, devient moins importante pour des excitations répétitives. La vibration axiale est peut-être un des facteurs favorisant de la fragilisation vertébrale.

- Pression intradiscale

Si l'on veut bien admettre avec KORESKA et al. 1977 (22), l'homogénéité, l'isotropie et l'état de contrainte hydrostatique du nucleus pulposus, alors la pression interne du noyau varie linéairement avec le tassement coaxial. Cependant l'étude sur dix disques humains non dégénérés réalisée par BORTOLUSSI, DOSDAT et ROBERT 1979 (3) semble montrer un comportement non hydrostatique du noyau.

Mais c'est à NACHEMSON et EVANS 1964 (25) que sont dus les meilleurs renseignements sur la pression intradiscale. Ces auteurs introduisirent par voie lombaire, chez l'homme vivant, un microcapteur de pression en position intranucléaire. Les enregistrements sont obtenus sur 19 sujets en position debout, assise, ou allongée en décubitus latéral. Quelques volontaires portent également des masses de 9 ou 20 kilogrammes. D'autres enfin sont porteurs d'un corset gonflable dont la pression est élevée jusqu'au maximum supportable par le patient. Aussi souvent que cela est possible, les sujets effectuent une manoeuvre de VAL SALVA (manoeuvre réalisée chez les lombalgiques). Les résultats de cette expérience sont très riches d'enseignements :

- les pressions intradiscales sont plus élevées chez le sujet assis (12 à 13 kg/cm^2 (13.10^5 Pa) que chez l'homme debout, 8 à 9 kg/cm^2 (8-9.10^5 Pa). Mais si ce même sujet debout porte un corset gonflé, la pression diminue à 7 kg/cm^2 (7.10^5 Pa). Il n'est pas étonnant de trouver les valeurs les plus faibles 4 à 5 kg/cm^2 chez l'individu en décubitus latéral.
- Lorsque les sujets sont porteurs de poids, les pressions intradiscales augmentent considérablement : 16 kg/cm^2 (masse de 9 kg), 20 kg/cm^2 (masse de 20 kg) chez les sujets assis.

Considérant que 57 % du poids du corps s'exerce sur L3 et 59 % sur L4, les auteurs montrent, à partir d'études réalisées sur le cadavre, que le port d'une masse d'une vingtaine de kilogrammes entraîne une charge de 1200 N sur la troisième vertèbre lombaire d'un sujet de 70 kg !

PANJABI 1978 (29) donne une explication du phénomène en considérant que la somme des forces appliquées au disque est réalisée par :

- la masse corporelle située au-dessus du disque.
- Les précontraintes liées à l'activité propre des muscles paravertébraux.
- Un moment de flexion dont le bras de levier est constitué par la projection du centre de gravité sur la perpendiculaire, passant par l'axe de la vertèbre.

Cependant, IGNAZI, COBLENTZ, HENNION, PRUDENT 1974-75 (15) montrent que le centre de gravité de l'être humain mesuré à l'aide d'un pendule composé se situe en regard de la deuxième ou troisième vertèbre sacrée à l'intersection des directions principales des cols des fémurs. La composante de charge liée au moment de flexion serait très faible, tout au moins chez l'homme debout. Un calcul simple montre alors que la force développée par les muscles sur L4 par un sujet debout porteur d'une masse de 20 kg est de 600 N environ.

- Etude en compression

C'est sans doute sur la compression discale que la littérature est la mieux documentée - BERKSON et al. 1979 (2), BORTOLUSSI et al. 1979 (3), HIRSCH et NACHEMSON 1954 (13), JAYSON et col. 1973 (16), KORESKA et al. (22), MARKOLF et MORRIS 1974 (23), MORRIS 1973 (24), NACHEMSON et col. 1964 (25), PANJABI-BRAND-WHITE 1976 (28), PANJABI et al. 1978 (30), SCHULTZ et col. 1979 (46).

La force de compression se transmet d'un plateau à l'autre par l'intermédiaire de l'anneau fibreux et du nucleus pulposus. Celui-ci suffisamment humide semble bien avoir un comportement hydrostatique. La pression créée dans cet organe pousse les structures voisines de façon homogène dans toutes les directions. Ici apparaît l'utilité des plateaux cartilagineux qui se comportent comme les couvercles concaves d'une boîte de conserve cylindrique dont l'intérieur est en surpression.

Lors de la compression du disque intervertébral, l'anneau fibreux est déformé vers l'extérieur. Les plateaux cartilagineux sont éloignés l'un de l'autre surtout en leur centre. Ils tendent à devenir convexes. Les expériences de compression montrent que le disque a un comportement de matériau viscoélastique : la relation entre la charge de compression axiale et la déformation est une relation exponentielle. A déformation constante, il existe une diminution rapide de la force appliquée pendant la première phase.

Les contraintes à l'intérieur d'un anneau ne s'exercent pas toutes dans la même direction. Il existe des efforts axiaux et des efforts tangentiels dits circonférentiels qui s'exercent dans le sens des fibres. Dans un disque sain, la répartition homogène des pressions en relation avec l'hydratation du nucleus, fait qu'il n'existe que des tensions à la périphérie de l'anneau, des tensions tangentielles et des compressions axiales dans les couches les plus centrales. L'application d'une force trop importante sur un segment vertébral tend à augmenter la convexité des plateaux cartilagineux, puis les effondrer pour créer la survenue de hernies intraspongieuses. Il s'agit donc d'une pathologie survenant chez un sujet jeune et il est bien classique de chercher la présence de nodule de Schmorl dans les séquelles de la maladie de Scheuermann.

La situation est tout autre quand le disque dégénère en se déshydratant. Le nucleus devient incapable de répartir les pression de façon homogène. Le mécanisme des forces est alors significativement modifié. Les plateaux cartilagineux subissent des forces d'égale amplitude tant en leur centre qu'en leur périphérie. Les contraintes axiales s'exercent en compression aussi bien à la périphérie de l'anneau que dans les lames fibreuses les plus internes. Seules, les tensions circonférentielles persistent à la périphérie. Les contraintes circonférentielles centrales sont aussi devenues des compressions de forte amplitude. Les conditions sont réunies pour l'apparition de ruptures dans la paroi ligamentaire du disque avec énucléation du noyau à travers la zone la moins épaisse, c'est-à-dire vers l'arrière (étiologie des sciatiques).

- Etude en flexion, extension, inflexion latérale, torsion

Des travaux ont fait l'objet d'une publication par SCHULTZ, WARWICK, NACHEMSON 1979 (46). Ils appliquent des forces et différents moments sur 42 segments vertébraux prélevés sur des cadavres frais. L'expérience est conduite avec ou sans précontrainte initiale. Les enregistrements montrent que le disque lombaire est moins flexible en torsion qu'en inflexion latérale (1,4° de rotation pour un moment de torsion de 10,6 Nm, et 5° en inflexion latérale pour une même valeur de moment de flexion). (La flexibilité est la valeur du déplacement rapporté à une charge unitaire : elle s'exprime en 0°/Nm pour la translation, c'est donc approximativement l'inverse de la raideur).

Dans le tableau n° 1 sont consignés les résultats de SCHULTZ et al. en degrés, pour des moments de 4,7 Nm et 10,6 Nm.

	MOMENTS			
MOUVEMENTS	4,7 Nm		10,6 Nm	
FLEXION	5,89	3,02	5,93	0,67
EXTENSION	3,64	1,02		
FLEXION LAT. DROITE	4,39	1,37		
FLEXION LAT. GAUCHE	4,00	1,82	4,68	0,77
TORSION	1,72	0,41	2,28	0,77

TABLEAU 1 : Etude des mouvements des disques intervertébraux (les résultats sont donnés en degrés)

Il existe également des mouvements de couplage (apparition de mouvements dans des directions différentes de celle de la force ou du moment appliqué). Les résultats sont consignés dans le tableau n° 2 qui se lit de la façon suivante : pour une flexion de 5,9 ° la translation à gauche vaut 0,3 mm et la torsion 0,4°.

MOMENTS 10,6 Nm	TRANSLATION (cm)			ROTATION (deg)		
MOUVEMENTS	GAUCHE	POST	SUP	FLEXION	INFLEXION G	TORSION
FLEXION	0,03	-0,20	0,03	5,9	-0,2	0,4
EXTENSION (4,7 Nm)	0,02	+0,10	-0,07	-3,6	0,4	-0,0
INFL. LAT. DROITE	-0,76	0,03	-0,00	0,2	-5,0	-0,1
INFL. LAT. GAUCHE	0,17	-0,04	-0,05	-0,8	4,7	-0,3
TORSION	0,06	0,03	0,00	-0,6	-0,1	-2,3

TABLEAU 2 : mouvements de couplage exercés sur le disque intervertébral.

Le tableau montre clairement que les mouvements d'inflexion latérale et de torsion sont couplés. Il a souvent été affirmé (et non démontré) que ces couplages sont inhérents à la structure de la colonne vertébrale.

Les auteurs discutent le rôle de l'activité musculaire paravertébrale et abdominale sur ces différents mouvements de la colonne. La surface de section utile des muscles abdominaux dans la relation envisagée est de 5 cm^2 , la surface de section des muscles érecteurs de la colonne est de 25 cm^2 . Alors que ces derniers agissent avec un bras de levier de 5 centimètres, les abdominaux agissent avec un bras de levier de 15 centimètres. Sachant que la possibilité maximale de la contraction musculaire volontaire humaine se situe entre 40 et 100 N/cm^2 et en utilisant la plus faible valeur 40 N/cm^2 , il apparait que des charges de 30 Nm sont nécessaires à la flexion et 50 Nm à l'extension. La comparaison des moments nécessaires ainsi calculés avec les résistances enregistrées expérimentalement montre que, seule, une petite partie des forces disponibles est utilisée pour vaincre les résistances aux mouvements (pour obtenir une flexion de 3°" à 5°" il suffit d'appliquer une charge de 10 Nm).

Ce calcul n'est que la quantification d'un phénomène d'observation courante : si les muscles du tronc peuvent vaincre des charges importantes, c'est qu'une faible partie de leur capacité est utilisée à vaincre les résistances internes.

- Etude en cisaillement

Les mêmes auteurs (BERKSON et al. 1979) (2) étudient l'amplitude des cisaillements postérieur, antérieur, latéral d, pour diverses forces appliquées dans l'axe vertical normal de compression (tableau n° 3).

		DEPLACEMENTS (cm)			
		COMPRESSION	CISAILLEMENT POSTERIEUR	CISAILLEMENT ANTERIEUR	CISAILLEMENT LATERAL D.
FORCES (N)	86	0,010	0,084 + 0,030	0,094 + 0,026	0,076 + 0,027
	145	0,019	0,124 + 0,021	0,142 + 0,046	0,111 + 0,050
	400	0,050 0,026			

TABLEAU 3 : (Explications dans le texte).

Ces résultats sont intéressants car les mouvements de cisaillement sont responsables en partie de la pathologie des luxations vertébrales.

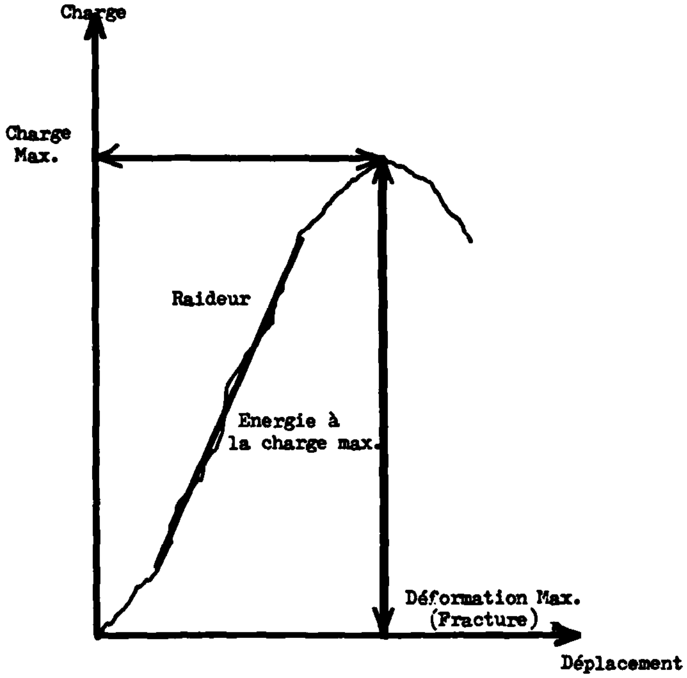
Cependant, la discussion de ces résultats est assez délicate et celle des auteurs est somme toute assez peu convaincante. En effet, l'étude des mouvements de couplage montre que les déplacements en translation (cisaillement) s'accompagnent de mouvements de flexion, extension, rotation. C'est ainsi que l'amplitude des mouvements obtenus n'est que rarement corrélée à la morphologie des pièces soumises à l'expérience : par exemple, la hauteur des disques ne semble avoir aucune conséquence sur les déplacements mesurés, ce qui ne manque pas de surprendre !

3.2 - CARACTERISTIQUES BIOMECANIQUES DES CORPS VERTEBRAUX : ETUDE DE KAZARIAN ET GRAVES 1979

Les caractéristiques mécaniques du tissu osseux vertébral ont été particulièrement étudiées par l'équipe de biodynamiciens des laboratoires de recherches de médecine aéronautique de l'US AIR FORCE. KAZARIAN, BOYD, Von GIERKE 1971 (17) KAZARIAN, Von GIERKE 1971 (18) KAZARIAN 1978 (20) KAZARIAN, BELK 1979 (21).
L'intérêt montré par ces chercheurs pour le comportement mécanique de la vertèbre est en relation avec les problèmes pathologiques présentés par les pilotes lors des évacuations de bord.

Il faut se souvenir que l'os est un organe en perpétuel remaniement. Sa formation est liée à l'existence d'une matrice protéique sur laquelle se dépose un complexe microcristallin d'hydroxyapatite (calcium et phosphate), ainsi qu'une petite quantité de carbonate de calcium. Les composés minéraux (cristaux d'apatites) sont caractérisés par une raideur élastique, une résistance en compression élevée et une résistance à la tension faible. Les fibrilles de collagène n'ont aucune résistance à la compression, mais présente une forte résistance à la traction, KAZARIAN et al. 1971 (17).

L'os est un système dynamique stable : l'activité ostéoblastique est à tout moment exactement contrebalancée par l'activité ostéoclastique. Les ostéoclastes exerçent leur pouvoir de résorption sur les cellules osseuses adultes, les ostéocytes. Il est aisément compréhensible que toute activité désordonnée de ces cellules (troubles d'origine cellulaire, vasculaire ou métabolique) entraine une rupture d'équilibre physiologique et par conséquent des variations des propriétés mécaniques. L'âge, les variations endocrine ou métabolique liées aux sexes, les pathologies métaboliques et endocriniennes, etc... sont les facteurs de troubles plus fréquents. KAZARIAN et GRAVES 1979 (21) ont particulièrement étudié les caractéristiques de résistance des corps vertébraux de la colonne vertébrale de macaques.



Graphe charge v.s. déplacement
(KAZARIAN) (21)
Figure 5

Les études sont réalisées sur les corps vertébraux dont le niveau de prélèvement réalise quatre groupes : D8 D9 D10 , D11 D12 L1, L2 L3 L4, L5 L6 L7. Les vertèbres de chacun des groupes sont supposées identiques. Elles sont prélevées sur 4 singes ; soit 48 vertèbres étudiées. Dans le plan expérimental, les vertèbres sont tirées au hasard. Chaque vertèbre d'un groupe est soumise à une compression à vitesse constante.

$R_2 = 8,89.10^{-5}$ m/s $\quad$ $R_4 = 8,89.10^{-3}$ m/s $\quad$ $R_6 = 8,89.10^{-1}$ m/s

Une seconde expérience est réalisée avec les vitesses intermédiaires.

$R_1 = 8,89.10^{-6}$ m/s $\quad$ $R_3 = 8,89.10^{-4}$ m/s $\quad$ $R_5 = 8,89.10^{-2}$ m/s

Les quatre paramètres (charge à la rupture, déformation à la charge de rupture, raideur, énergie nécessaire pour obtenir la fracture du corps vertébral) sont obtenus directement à partir de la courbe établie sur la figure 5. Certaines grandeurs données en unité industrielle de contrainte et de déplacement dépendent à la fois de la courbe charge-déformation et des données géométriques du spécimen :

- Contrainte Max industrielle $= \frac{\text{Force à la rupture}}{\text{surface du spécimen}}$
  (traduction litérale)

$$\text{déformation max industrielle} = \frac{\text{déformation à la charge de rupture}}{\text{longueur initiale du spécimen}}$$

$$- \text{ module d'élasticité} = \text{raideur (N/m)}. \frac{\text{longueur initiale du spécimen (m)}}{\text{surface } (m^2)}$$

RESULTATS

* La charge à la rupture : les effets conjugués des vitesses de déplacement et de la position interviennent sur la valeur de la charge nécessaire pour provoquer la fracture

pour D8 D9 D10 à $8,89.10^{-3}$ m/s : 3000 N

L5 L6 L7 à $8,89.10^{-1}$ m/s : 7500 N

La charge de rupture est une fonction linéaire du logarithme de la vitesse (à une constante près) significative du niveau vertébral considéré.

* Déformation à la charge de rupture : les résultats montrent une dispersion beaucoup plus importante que dans le cas précédent. Cependant, les valeurs de déformation à la charge de rupture sont en liaison avec les effets conjugués de la vitesse d'application, de la force, du niveau vertébral.

* Raideur : les raideurs les plus élevées sont obtenues avec la charge la plus forte appliquée aux vitesses les plus élevées.

pour D8 D9 D10 $2,02.10^{6}$ N/m

D11 D12 L1 $2,81\ 10^{6}$ N/m

L2 L3 L4 4.10^{6} N/m à vitesse élevée $8,89.10^{-1}$ m/s

1.10^{6} N/m à vitesse lente $8,89.10^{-5}$ m/s

* Energie à la charge de rupture : si l'effet de la vitesse d'application des forces n'est pas significative quand aux variations de l'énergie absorbée, par contre, le niveau vertébral intervient. Ordre de grandeur D11 D12 L1 - L2 L3 L4 : 8 joules.

* Contrainte industrielle maximale : l'ordre de grandeur à vitesse moyenne quel que soit le niveau vertébrale est de 19.10^{6} Pa.

* Déformation industrielle à la contrainte maximale : la déformation à la charge maximale divisée par la hauteur initiale du specimen (m/m) est d'environ 0,22 en D11 D12 L1 pour les vitesses moyennes. La vitesse de déplacement et l'effet du niveau vertébral sont significatifs au seuil de sécurité de 0,95.

* Module d'élasticité : le module d'élasticité varie en fonction des vitesses d'application des forces et du niveau vertébral. Pour une vitesse d'application moyenne $8,89\ 10^{-3}$m/s le module d'élasticité en D8, D9, D10 est égal à 120.10^{6} Pa et en L2 L3 L4 à 220.10^{6} Pa.

3.3 - PROPRIETES BIOMECANIQUES DES LIGAMENTS INTERVERTEBRAUX

Quand la géométrie de la structure à étudier est aussi perturbée que celle du segment vertébral, la méthode d'étude la plus simple est de comparer les résultats obtenus en présence et en l'absence du composant dont on désire connaître le comportement biomécanique. C'est la raison pour laquelle NACHEMSON, BERKSON et SCHULTZ 1979 (46) font les expériences identiques à celles rapportées précédemment, mais cette fois-ci les arcs postérieurs des deux éléments de l'unité vertébrale sont intacts. Il convient donc de comparer les données rapportées ici à celles obtenues uniquement en présence des corps vertébraux en se souvenant qu'il s'agit d'études réalisées sur des pièces anatomiques composées d'au moins un segment vertébral (un disque et les deux vertèbres adjacentes).

Notons cependant, que les courbes force-déformation rendent compte des propriétés physiques du ligament en tant que structure quand les expériences sont conduites sur des ligaments intacts. La charge de rupture s'exprime en newton. Lorsque les expériences sont conduites sur des échantillons de taille standard prélevés sur un ligament, les données recueillies ne rendent plus compte des caractéristiques de la structure elle-même, mais du matériau constitutif du ligament. Les courbes force-déformation sont remplacées par des courbes contrainte-déformation et les grandeurs de rupture sont homogènes à une pression (N/m^2).

- Etude de la flexibilité

Mouvements principaux résultant de l'application de moments de flexion ou de torsion (éléments postérieurs intacts).

	MOMENTS	
VALEURS EN DEGRES	4,7 Nm	10,6 Nm
FLEXION	5,13 ± 1,86	5,51 ± 1
EXTENSION	2,12 ± 0,98	2,99 ± 1,02
FLEXION LAT. DROITE	4,47 ± 1,63	5,64 ± 1,22
FLEXION LAT. GAUCHE	4,32 ± 1,47	4,90 ± 0,79
TORSION	0,69 ± 0,33	1,50 ± 0,67

TABLEAU 4 : (valeurs en degrés)

- Pression intradiscale

Influence d'un mouvement de flexion ou de torsion

Elévation de pression intranucléaire sous l'effet de l'application de moments de flexion ou de torsion (éléments postérieurs intacts - pression initiale 262 KPa sous 400 N).

	MOMENTS	
MOUVEMENTS	4,7 Nm	10,6 Nm
FLEXION	95 ± 71	267 ± 122
EXTENSION	52 ± 108	49 ± 202
FLEXION LAT. DROITE	121 ± 116	289 ± 140
FLEXION LAT. GAUCHE	126 ± 82	256 ± 134
TORSION	13 ± 22	32 ± 37

TABLEAU 5 : (valeur en KPa)

- Influence d'une force de compression ou de cisaillement

Variation de la pression intradiscale en réponse aux charges de compression et de cisaillement (éléments postérieurs intacts - pression intradiscale sous charge 109 143 KPa).

PRESSION INTRADISCALE SOUS CHARGE	86 N	145 N	400 N
COMPRESSION	51	86	251 ± 75
CISAILLEMENT POSTERIEUR	-6 ± 62	10 ± 85	
CISAILLEMENT ANTERIEUR	10 ± 19	38 ± 55	
CISAILLEMENT LATERAL DROIT	19 ± 26	45 ± 40	

TABLEAU 6 : (Valeur en KPa)

- Etude des mouvements de couplage

L'étude des mouvements de couplage (translation, rotation) est réalisée sous l'effet d'un moment de 10,6 Nm (éléments postérieurs intacts).

	TRANSLATION (cm)			ROTATION (degrés)		
	GAUCHE	POST.	SUP.	FLEXION	INFL. LAT. G.	TORSION
FLEXION	0,01	-0,17	0,02	5,5	-0,4	0,4
EXTENSION	0,02	-0,08	-0,04	-2,9	0,3	0,0
INFL. LAT. DR.	-0,21	0,08	-0,01	0,9	-5,9	0,2
INFL. LAT. G.	0,14	-0,05	-0,04	0,0	4,9	-0,1
TORSION	0,00	0,01	0,00	0,2	0,0	-1,4

TABLEAU 7

- Etude en compression et cisaillement

Mouvements principaux moyens en réponse aux charges de compression et de cisaillement (éléments postérieurs intacts).

	CHARGE		
DEPLACEMENT en cm	86 N	145 N	400 N
COMPRESSION	0,011	0,018	0,051 ± 0,024
CISAILLEMENT POST.	0,059 ± 0,029	0,085 ± 0,082	
CISAILLEMENT ANT.	0,060 ± 0,024	0,121 ± 0,038	
CISAILLEMENT LAT. DR.	0,067 ± 0,048	0,100 ± 0,039	

TABLEAU 8

La comparaison de ces données à celles obtenues en l'absence d'éléments postérieurs montre que :

a) l'élimination de l'arc vertébral provoque un accroissement approximatif de l'amplitude des mouvements de 70 à 150 % sous l'effet d'une charge de 4,7 Nm

b) sans charge initiale, les éléments segmentaires possèdent une pression intranucléaire moyenne de 109 KPa (éléments postérieurs intacts), de 76 KPa (éléments postérieurs excisés),
c) l'élévation de la pression intradiscale sous l'influence d'un moment de torsion ou de flexion est à peu près constante en cas de disparition des éléments postérieurs. Ceci est vrai en extension et en torsion ou ces mouvements provoquent une multiplication par deux ou trois de la pression initiale (sous charge de 400 N),
d) l'excision des éléments postérieurs n'a pratiquement pas d'effet sur les résultats de l'application de charge en compression, mais augmente la valeur des cisaillements de 10 à 60 %.

A l'issue de cette revue de la mécanique statique, des considérations générales relatives au comportement non pas statique, mais dynamique de la structure vertébrale peuvent être formulées. Des appréciations sur les paramètres à mesurer et par conséquent sur les capteurs à utiliser peuvent être envisagées.

Il se dégage des observations qui viennent d'être rapportées, l'idée que la résistance de l'os et des ligaments varie avec la vitesse d'application des forces, ainsi :
- les déformations lentes entraînent préférentiellement des ruptures osseuses plutôt que des déchirures ligamentaires,
- inversement, les déformations rapides provoquent préférentiellement des ruptures ligamentaires. (La résistance de l'os augmente relativement plus vite que celle du ligament quand la vitesse d'application des forces augmente),
- l'immobilisation affaiblit la résistance osseuse beaucoup plus vite que la résistance ligamentaire,
- si la rupture survient toujours au point le plus faible, celui-ci se trouve au niveau des plateaux cartilagineux chez l'adolescent, sur la portion postérieure de l'anneau chez l'adulte.

Tous ces faits sont bien vérifiés par les données cliniques de la pathologie vertébrale.

Cette étude bibliographique montre :
- d'une part, que peu d'expériences ont été réalisées in vivo en régime vibratoire (en matière de caractérisation d'unité vertébrale),
- d'autre part, que le comportement dynamique du disque est non linéaire.

Par conséquent :
- Pour travailler in vivo, il faut choisir un modèle animal.
- Pour caractériser l'unité vertébrale, il faut étudier les transmissibilités en fonction des fréquences ; donc faire l'étude de la fonction de transfert.
- Pour étudier une fonction de transfert, il est indispensable de travailler en régime linéaire, donc en déplacements faibles (approximation de Liapounov).
- Pour réaliser ce type d'acquisition, le choix de capteurs de force, de pression, de déplacement, ou d'accélération doit être fait en fonction de considérations qui ne sont pas uniquement technologiques mais également anatomiques et méthodologiques.

La force : c'est une grandeur qui s'étudie en série dans un système. S'il n'est pas envisageable de mettre un capteur de force dans le disque, il n'est pas exclu de le placer sur un muscle. NOGUES C. 1967 (27), mesure la force ventriculaire cardiaque à l'aide de jauges de contraintes. Cette technique se heurte à des difficultés majeures d'étalonnage ; mise en tension initiale de la jauge, détermination purement subjective d'un repos musculaire, résultats fonction de la quantité de faisceaux musculaires intéressés, etc...

La pression : l'obtention de la pression intranucléaire nécessite l'implantation du capteur dans le disque. Cette mesure, comme celle des forces ne permet pas d'obtenir la fonction de transfert désirée.

Les déplacements : l'obtention de l'élongation du disque intervertébral nécessite un montage en pont avec fixation sur deux vertèbres adjacentes. Des considérations intéressant le rapport signal/bruit font rejeter l'utilisation d'un tel capteur (petits déplacements vibratoires à mesurer, alors que le capteur doit posséder impérativement une grande dynamique de mesure en raison des grands débattements provoqués par les mouvements flexion-extension de l'animal).

L'accélération : l'étude de celle-ci est intéressante ; variant comme le carré de la fréquence elle peut atteindre des valeurs convenables même pour des déplacements faibles. Les accéléromètres peuvent s'implanter seuls sur les vertèbres, par conséquent ils délivrent des tensions électriques représentatives de signaux d'entrée et de sortie nécessaires à la détermination de la fonction de transfert des organes intervertébraux anatomiquement intacts.

4 - BIOMECANIQUE VERTEBRALE : DYNAMIQUE

Ces études sont ou ont été menées au Centre de Recherches de Médecine Aéronautique à Paris (QUANDIEU et Coll. (34), PELLIEUX et Coll. (32)) et dans la division de biodynamique et de bioenginierie du laboratoire de recherche de Médecine Aérospatiale de l'U.S.A.F. à Wright-Patterson (cf : article n° 18 du présent C.P.).

Les buts poursuivis sont :

1) - préciser les caractéristiques physiques, biodynamiques intrinsèques de la colonne ; étude des vitesses de phase, de groupe...

2) - Analyse des variations de ces vitesses et de ces fonctions de transfert soit :
- au cours de la variation de rigidité musculaire (hypothèse de la masse dynamique)
- lors des altérations de la structure elle-même.
  - ablation du nucleus pulposus chez l'animal aigu
  - ablation des apophyses articulaires chez l'animal aigu et l'animal chroniquement bioinstrumenté.

A l'heure actuelle - même si les résultats ne sont que parcellaires - l'ensemble du programme a été réalisé, selon un protocole qui obéit à trois considérations fondamentales : physiologiques, physiques et statistiques. Elles ont conduit à l'établissement de protocoles d'analyses de données relativement figés au plan expérimental mais qui restent toutefois suffisamment souples pour prendre en compte toutes les nouvelles acquisitions.

La technique (décrite par ailleurs (37)) consiste à recueillir les signaux délivrés par des accéléromètres miniatures implantés sur la colonne vertébrale de primates soumis à des vibrations (figure 6).

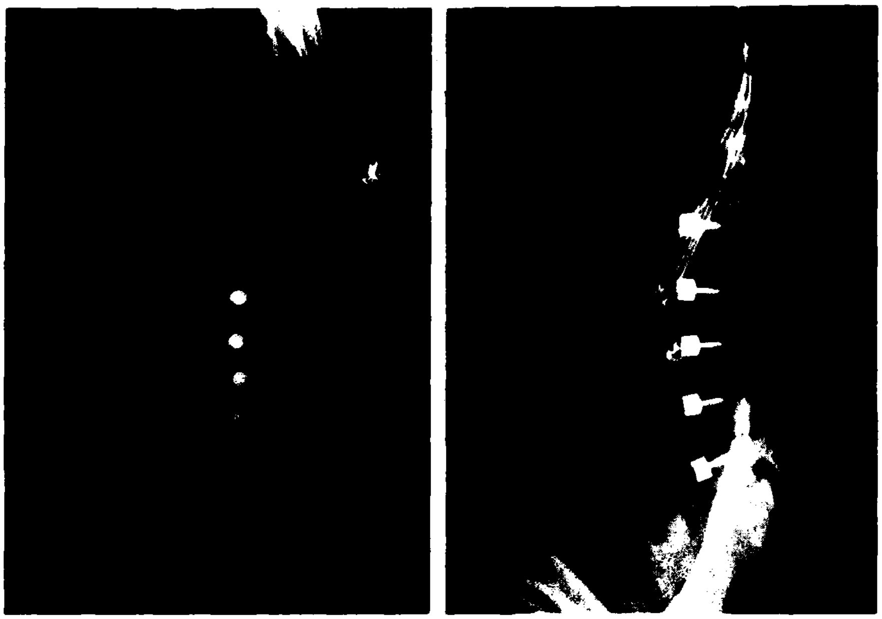


Figure 6 : Méthode d'enregistrement des vibrations des vertèbres chez l'animal vivant, par l'implantation d'accéléromètres miniatures.

Les signaux peuvent être traités dans le domaine temporel ou dans le domaine des fréquences (figures 7 et 8).

Les données obtenues permettent d'énoncer synthétiquement que les unités vertébrales se conduisent au plan dynamique comme :

1) - des filtres passe-bas

L'emploi de deux méthodes de bioinstrumentation, l'une aigue, l'autre chronique permet d'étudier :

- d'une part les caractéristiques dynamiques des éléments fondamentaux de la colonne - os ligaments - en suivant le devenir de la propagation d'une onde de vibration transitoire consécutive à l'application d'un choc sur le sacrum,
- d'autre part, le comportement global de la structure elle-même, lorsqu'elle est soumise à une vibration forcée.

De l'étude pratiquée en régime impulsionnel il ressort que :

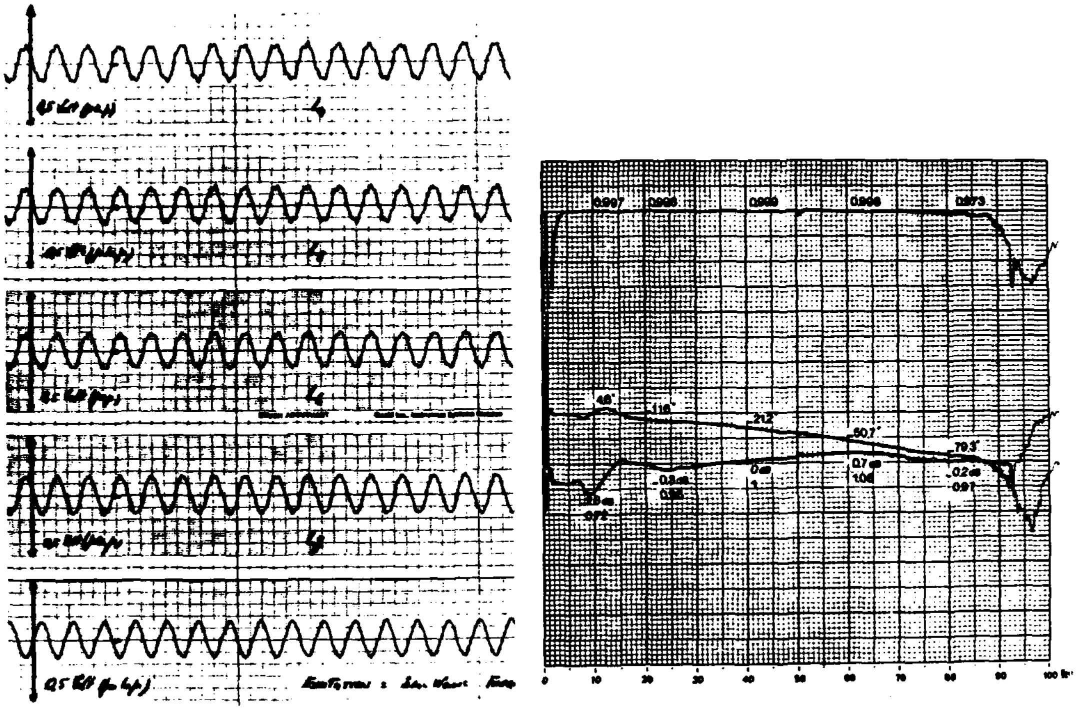
2) - les différents matériaux ostéoligamentaires de la colonne vertébrale sont dispersifs vis-à-vis de l'énergie mécanique,
3) - ce que prouve la variation de la vitesse de phase en fonction de la fréquence
4) - la vitesse du signal est faible dès que l'onde a franchi la barrière lombosacrée,
5) - pour une faible quantité d'énergie initiale, il n'existe pas d'onde réfléchie sur la charnière atloïdo-occipitale de l'onde incidente créée par l'impulsion appliquée sur le sacrum qui "redescende" jusqu'au niveau de la colonne lombaire.

De l'étude pratiquée en régime forcé il ressort que :

6) - l'articulation lombosacrée est une zone dynamiquement privilégiée en ce qu'elle présente des possibilités d'amplification importante des vibrations entre 10 et 15 Hz,

7) - les unités vertébrales lombaires basses se caractérisent par une bonne capacité d'amortissement tandis que

8) - les unités lombaires sus-jacentes se caractérisent par la possibilité de réduire à chaque niveau la largeur de la bande de fréquence transmise.



Figures 7 et 8 : Exemples de réponse vibratoire (à gauche) de la colonne vertébrale d'un animal bioinstrumenté selon la méthode indiquée figure 6 et assis sur une table vibrante (signal du bas). De haut en bas on lit les réponses de L7 - L6 - L5 - L4. A droite : exemple d'analyse obtenue sur une unité vertébrale d'un animal soumis à une vibration aléatoire dans une bande de fréquence située entre 0 et 100 Hz (lire de bas en haut : le module et la phase de la fonction de transfert, en haut la valeur de la fonction de cohérence).

Sur ces caractéristiques de base, il apparait que :

9) - la relaxation musculaire diminue le pouvoir d'amortissement de la charnière lombosacrée et

10) - la contraction musculaire déplace les phénomènes de résonance vers les plus basses fréquences.

Les altérations anatomiques de la structure entrainent ainsi qu'il est normal, des altérations des propriétés mécaniques.

L'ablation des nucleus pulposus provoque :

* au niveau de la charnière lombosacrée :

11) - un déplacement des phénomènes de résonance vers les plus hautes fréquences,

12) - une augmentation importante des modules des fonctions de transfert à la résonance,

13) - une diminution importante des possibilités d'amortissement dans la bande 40-80 Hz,

* sur l'ensemble de la colonne lombaire :

14) - une augmentation importante de la distorsion non linéaire.

L'ablation des facettes articulaires provoque sous les réserves qui seront explicitées dans l'article n° 15,

15) - une diminution globale et harmonieuse du pouvoir amortisseur des unités vertébrales.

16) - une amplification substantielle des phénomènes de résonance, mais semble-t-il sans glissement vers la droite de ces phénomènes.

Ainsi, par analogie, de la même façon qu'un ouvrage d'art est conçu en fonction des caractéristiques propres de ses matériaux constitutifs destinés, selon leur agencement, à construire cet ouvrage en respectant un cahier des charges préétabli, il est nécessaire de poursuivre la caractérisation des possiblités mécaniques dynamiques de la

poûtre maîtresse de la charpente corporelle humaine pour :
- déterminer les caractéristiques dynamiques des matériaux constitutifs,
- déterminer le comportement dynamique global du système.

Comment faire ?

Une vertèbre ne peut être isolée du rachis comme une barre d'acier peut l'être d'un pont ou d'un bâtiment pour être étudiée en laboratoire d'essai !

Toutefois, l'extrême largeur de la bande de fréquence utilisée a permis de montrer qu'en très haute fréquence (en impulsion) on se trouve dans le domaine de l'application de l'acoustique qui étudie le type privilégié d'oscillation propagée, flexion, compression, etc... en fonction de l'homogénéïté, de la géométrie, de la viscoélasticité... du matériau.

Avec les très basses fréquences et en régime forcé c'est la réponse globale de l'axe vertébromusculaire qui est analysée. On peut donc parler de deux bandes de fréquences d'intérêt "anatomohistologique" et "ergonomique".

Les ondes des hautes fréquences (supérieure à 1000 Hz) dont nous savons maintenant qu'elles se propagent dans l'axe vertébral (PELLIEUX (32)) sont d'intérêt "anatomohistologique" si l'on veut bien considérer qu'une oscillation à 4000 Hz présente - en fonction de sa vitesse de propagation - une demi longueur d'onde approximativement égale à la hauteur d'une vertèbre. Dès lors il faudra bien un jour s'intéresser à l'effet qu'une telle oscillation peut avoir, en son ventre, au niveau des cellules cartilagineuses et des plateaux vertébraux ou de la vascularisation à l'interface des disques et de l'os corporeal ; bref ! de l'importance de ces fréquences sur la génèse des processus ostéophytiques et spondylarthrosiques.

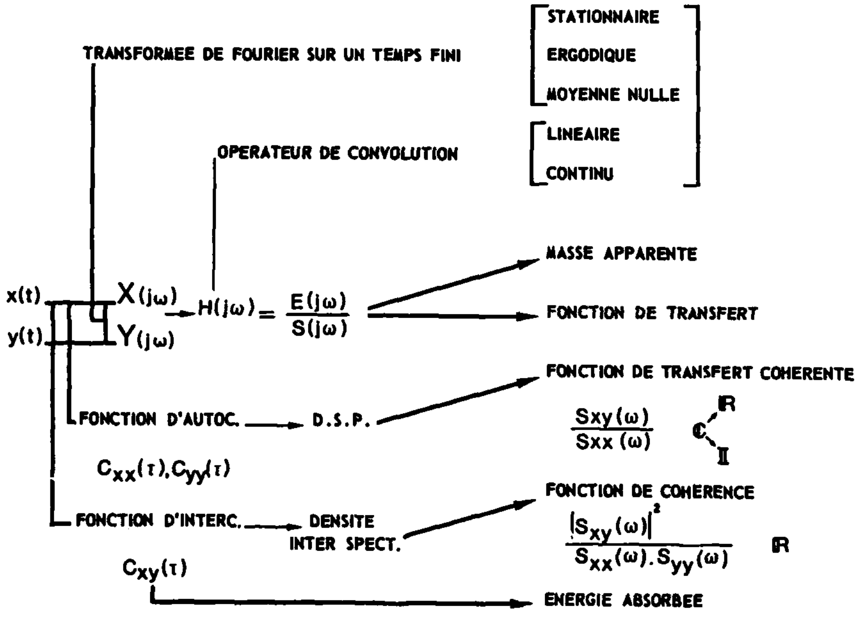


Figure 9 : Traitement effectué sur les signaux des accéléromètres implantés sur la colonne vertébrale. Conditions d'utilisation de la transformée de FOURIER sur un temps fini et conditions d'existence d'un opérateur de convolution.

Ces considérations ne préjugent en rien du comportement de la structure globale soumise à de très basses fréquences. Celles-ci sont évidemment d'intérêt ergonomique puisqu'elles sont rencontrées chaque jour en milieu civil, dans les conditions d'utilisation des moyens technologiques modernes, industriels, véhicules de transport, engins de chantiers et lors de l'utilisation d'aéronefs à voilure tournante, avions d'armes, engins blindés, etc... en pratique militaire.

Après l'étude de la statique et résistance des matériaux, de la la dynamique, il reste à aborder l'étude de la géométrie du mouvement c'est-à-dire, en langage mécanique, de la cinématique. Il ne saurait être question de citer ici les nombreux auteurs qui se sont intéressés aux mouvements de la colonne abstraction faite des forces qui les produisent. Nous ne rapporterons, en raison de sa haute valeur d'exemple méthodologique qu'une seule étude concernant les centres instantanés de rotation.

IV - EXEMPLE D'ANALYSE CINEMATIQUE :

RECHERCHE DE LA PRECISION OPTIMALE DANS L'ETUDE DE LA CINEMATIQUE DES ARTICULATIONS VERTEBRALES : ETUDE RADIOGRAPHIQUE (DIMNET J., - 1980) (8)

Il existe une contradiction entre le caractère continu des mouvements articulaires de la colonne vertébrale et la fixité indispensable à l'obtention des radiographies.

Si les documents radiographiques sont obtenus au cours d'un mouvement (inflexion latérale par exemple), il convient de déterminer des paramètres géométriques, autres que des points, dont l'analyse optimale des déplacements permet l'étude précise de la cinématique vertébrale.

Habituellement :

- l'opérateur identifie plusieurs détails ponctuels puis mesure le vecteur déplacement de chacun de ces points,
- pour reconstituer la cinématique du déplacement articulaire *entre deux clichés*, les relations utilisées sont celles de la cinématique continue. Elle implique que tous les vecteurs déplacements soient *à priori considérés comme infiniment petits*,
- les résultats donnés sont souvent délivrés sans marge d'incertitude.

L'auteur propose :

- de déterminer des paramètres autres que des points qui délivrent des résultats avec une dispersion la plus faible possible,
- de considérer comme finis les déplacements des vertèbres entre deux clichés,
- d'accompagner les résultats d'une marge d'incertitude.

1 - PARAMETRE GEOMETRIQUES

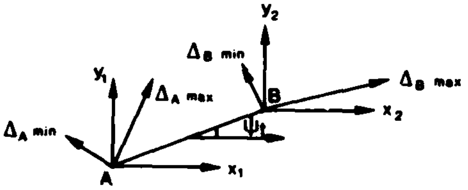
Les radiographies sont placées sur une tablette à digitaliser, reliée à un microordinateur PDP 11/05. Après la saisie des données et leur enregistrement, les valeurs sont soumises à divers traitements.

La cinématique définie ultérieurement prend en compte les glisseurs unitaires de ces directions.

Quelle est l'incertitude affectée à un axe naturel défini par les coordonnées du bipoint AB ?

Pour chaque bipoint A B les coordonnées $\begin{Bmatrix} x_{Ai} \\ y_{Ai} \end{Bmatrix}$ $\begin{Bmatrix} x_{Bi} \\ y_{Bi} \end{Bmatrix}$ sont enregistrées, est calculé par l'intermédiaire de sa tangente Ψ_i

$$t_g\, \Psi_i = \frac{y_{Bi} - y_{Ai}}{x_{Bi} - x_{Ai}}$$



Pour les N mesures de bipoints il est possible de définir

- une matrice d'incertitude pour A,
- une matrice d'incertitude pour B,
- une incertitude angulaire $\Delta\Psi$

$$\Delta\Psi = \sqrt{\Sigma_{i=1}^{n} \frac{\Psi_i - \Psi_M}{n}}$$

2 - LA CINEMATIQUE DES DEPLACEMENTS FINIS DE SOLIDES CONNUS PAR LEURS AXES NATURELS

Quels sont les éléments cinématiques caractéristiques des déplacements entre deux clichés successifs ?

a) Déplacement spatial

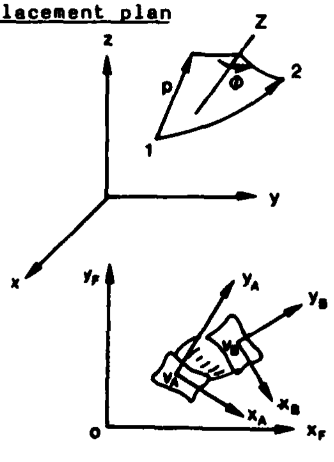
Le déplacement de la vertèbre de la position 1 à la position 2 est défini comme un déplacement hélicoïdal dont la position de l'axe est variable en fonction du temps.

Les éléments cinématiques caractéristiques d'un tel mouvement sont :

- l'axe de vissage Z,
- la rotation
- le glissement p.

L'auteur propose de ne pas faire intervenir un déplacement de points, qui présente une trop grande incertitude, mais d'étudier le déplacement des axes naturels connus avec une plus grande précision.

b) Déplacement plan



L'auteur lui accorde une plus grande importance car il ne nécessite qu'une seule série de clichés, au contraire des déplacements spatiaux qui exigent une reconstitution des formes dans l'espace à partir de deux séries de clichés.

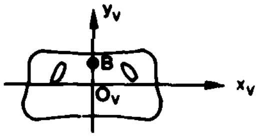
Dans le plan, le vissage est dégénéré en une rotation.

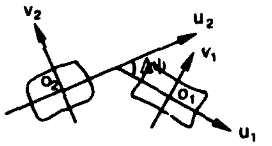
De plus, le seul déplacement relatif de V_A/V_B est digne d'intérêt. Mais il peut être obtenu avec une grande précision et étudié par l'intermédiaire des déplacements absolus.

V_A/ repère fixe.

V_B/ repère fixe.

Dans le cas des déplacements finis et des déplacements infiniment petits, il convient de déterminer le déplacement angulaire $\Delta\Psi$ et la position du centre de rotation.





Sur un corps vertébral, un référentiel est déterminé par l'axe X_V tangent au bord inférieur des pédicules et Y_V orthogonal au premier en O.

Le déplacement angulaire $\widehat{\vec{u}_1\vec{u}_2} = \Delta\Psi$ est tel que :

$$\vec{Z}\ \mathrm{tg}\ \frac{\Delta\Psi}{2} = \frac{(\vec{u}_2 + \vec{u}_1)\ \Lambda (\vec{u}_2 - \vec{u}_1)}{(\vec{u}_1 + \vec{u}_2) . (\vec{u}_1 + \vec{u}_2)} \quad \text{(Formule de Rodrigues)}$$

dans lequel :

$\vec{Z}$ vecteur unitaire de l'axe orthogonal au plan de la radio.

$$\vec{u} \begin{cases} \vec{u}_1 & \text{au temps } t_1 \\ \vec{u}_2 & \text{au temps } t_2 \end{cases}$$

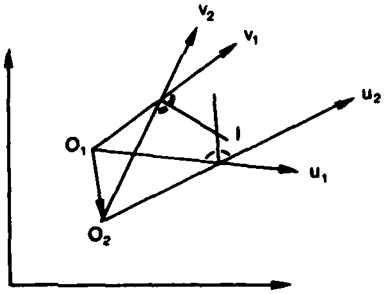
Dans le cas des déplacements infiniment petits, il vient comme déplacement angulaire.

$$2\ d\ \Psi = \frac{\vec{u}\ \Lambda\ \vec{du}}{\vec{u}.\vec{u}}$$

u : vecteur unitaire
du : vecteur déplacement
dΨ : rotation infinitésimale

La position du centre de rotation I est connue en appliquant la formule de Rodrigues au déplacement de direction $\vec{u}$, $\vec{v}$ tq $\vec{u}_1$, $\vec{v}_1 \rightarrow \vec{u}_2$, $\vec{v}_2$ de centre O tq $O_1 \rightarrow O_2$.

$$\vec{OI} = \frac{1}{\mathrm{tg}\ \frac{\Psi}{2}} \cdot \frac{\vec{Z}\ \Lambda (\vec{mu}_2 - \vec{mu}_1)\ \Lambda\ (\vec{v}_2 - \vec{v}_1) + (\vec{u}_2 - \vec{u}_1)\ \Lambda\ (\vec{mv}_2 - \vec{mv}_1)}{(\vec{u}_2 - \vec{u}_1).(\vec{v}_2 + \vec{v}_1)}$$



I : intersection des bissectrices extérieures de I et K

$$\vec{mu}_1 = \vec{OO}_1\ \Lambda\ \vec{u}_1$$
$$\vec{mu}_2 = \vec{OO}_2\ \Lambda\ \vec{u}_2$$
$$\vec{mv}_1 = \vec{OO}_1\ \Lambda\ \vec{J}_1$$
$$\vec{mv}_2 = \vec{OO}_2\ \Lambda\ \vec{k}$$

Dans le cas des déplacements infiniment petits, la *même* construction géométrique peut-être utilisée

$$\vec{u}_2 - \vec{u}_1 = \vec{du}$$
$$\vec{v}_2 - \vec{v}_1 = \vec{dv}$$

I est localisé à la fois sur les perpendiculaires à $\vec{du}$ et $\vec{dv}$ tracées par K et I respectivement.

3 - OBTENTION DES CENTRES DE ROTATION RELATIFS (PARAMETRES DES MOUVEMENTS RELATIFS D'UNE VERTEBRE PAR RAPPORT A L'AUTRE

Habituellement les calculs des déplacements finis relatifs de B/A (respectivement A/B) utilisent les positions relatives de B par rapport à A par l'intermédiaire de coordonnées de points.

Mais cette méthode comporte une grande part d'imprécision sur B et sur A.

L'auteur préfère obtenir directement les grandeurs cinématiques relatives à l'aide des valeurs des paramètres cinématiques absolus (mouvement de B et de A rapportés au référentiel fixe : celui de la tablette à digitaliser. (Justification : Thèse Dr ès Sciences DIMNET, 1978)

a) <u>Détermination de l'ellipse d'incertitude concernant la localisation d'un point</u>

Pour un même point, N relevés sont effectués.

On définit alors :

- **Le Barycentre M des N points.** $x_M = \frac{1}{N}\ \Sigma_{i=1}^{n}\ x_i \qquad y_M = \frac{1}{N}\ \Sigma_{i=1}^{n}\ x_i$

- **La matrice d'incertitude E** $E = \begin{bmatrix} E_x & E_{xy} \\ E_{xy} & E_y \end{bmatrix}$

dont les coefficients E_x, E_y, E_{xy} sont issus de la méthode des moindres carrés.

$$E_x = \frac{1}{N} \Sigma_{i=1}^{n} (x_i - x_M)^2 \qquad E_y = \frac{1}{N} \Sigma_{i=1}^{n} (y_i - y_M)^2 \qquad E_{xy} = \frac{1}{N} \Sigma_{i=1}^{n} (x_i - x_M)(y_i - y_M)$$

Pour une direction d'un vecteur unitaire $\vec{u} = \left\{ \cos \Psi \quad \sin \Psi \right\}$ l'incertitude Δu est donnée par :

$$\vec{u} = \begin{Bmatrix} \cos \Psi \\ \sin \Psi \end{Bmatrix} \quad \Delta u = \sqrt{u\, [E]\, u^{-}} = \left[\left\{ \cos\Psi,\ \sin\Psi \right\} \begin{bmatrix} E_x & E_{xy} \\ E_{xy} & E_y \end{bmatrix} \begin{Bmatrix} \cos\Psi \\ \sin\Psi \end{Bmatrix} \right]^{\frac{1}{2}}$$

Pour les directions de x, y les imprécisions sont $\Delta x \quad \Delta y$.

$$\Delta x = \sqrt{\{1,0\}\ [E] \begin{Bmatrix} 1 \\ 0 \end{Bmatrix}} \qquad \Delta y = \sqrt{\{0,1\}\ [E] \begin{Bmatrix} 0 \\ 1 \end{Bmatrix}}$$

Ainsi, à la lecture d'un même point, il est possible d'associer une ellipse d'incertitude dont les axes sont sur la direction des vecteurs propres associés aux valeurs propres de la matrice et dont le centre est le point moyen.
Le nombre N de lectures est celui qui minimise la surface de cette ellipse d'incertitude. Des essais systématiques ont montré que 20 < N < 30.

b) <u>Incertitude relative à la position d'un axe naturel</u>
Alors que sur un os, il n'existe pas de points géométriques identifiables, il est possible de demander à un observateur de définir l'axe d'un os ou de préciser une direction naturelle : c'est ainsi que les mesures angulaires les plus précises sur la colonne vertébrale utilisent les directions des plateaux vertébraux. L'auteur a systématiquement eu recours à des directions qui sont acquises par des bipoints.

La construction du centre de rotation relatif est donnée sur la figure ci-dessous :

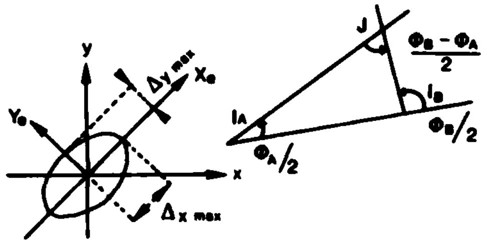
I_A : centre de rotation absolu de A

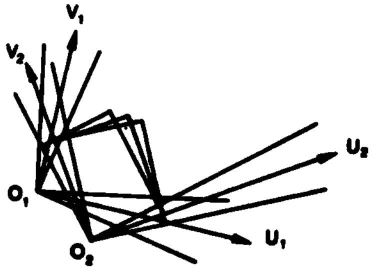
I_B : centre de rotation absolu de B

J : centre de rotation relatif A/B

ϕ_A; ϕ_B : déplacement angulaire de A et B par rapport au solide fixe

ϕ_B; ϕ_A : déplacement relatif de B/A par rapport à A supposé fixe





Notons que les trois centres de rotation I_A, I_B et J ne sont pas colinéaires (contrairement au cas des déplacements infiniment petits).
Ayant ainsi défini des paramètres autres que ceux généralement reconnus sur une radio, l'auteur se propose de déterminer l'incertitude liée à la précision des centres de rotation.
L'imprécision sur la position de l'origine est négligée (intersection de deux axes naturels).
Il existe une imprécision sur la position angulaire des vecteurs de la base u_1 v_1, u_2 v_2, soit une amplitude angulaire $\Psi + \Delta\Psi$
Au temps t_1 : 3 possibilités : $\Psi_1 - \Delta\Psi_1, \Psi_1, \Psi_1 + \Delta\Psi_1$
Au temps t_2 : 3 possibilités : $\Psi_2 - \Delta\Psi_2\ \Psi_2, \Psi_2 + \Delta\Psi_2$

Il existe donc une nuée de 9 centres de rotation I, possibles. Il est alors possible de définir la position moyenne du centre (barycentre des neuf centres) et un cercle de dispersion équivalent à la nuée des centres.

Les combinaisons possibles de 9 centres absolus conduit à 81 centres relatifs sur lesquels on détermine de nouveau l'incertitude.
Finalement l'auteur propose la méthode d'analyse suivante :

1) - n'étudier que les déplacements plans (gain sur le nombre de radiographies et diminution de l'irradiation des sujets soumis à l'examen),
2) - choisir la position des vecteurs de base assignés à chaque os en fonction de ses propriétés anatomiques,
3) - calculer les centres de rotation absolus et relatifs pour chaque couple d'os et pour chaque déplacement élémentaire,
4) - déterminer le nombre de radiographies nécessaires et optimiser en fonction des données obtenues sur les cercles de dispersion.

V-<u>PERSPECTIVES</u>

La connaissance de données fondamentales concernant la mécanique vertébrale est indispensable à la poursuite des travaux selon deux directions naturelles : le développement de modèles et l'exploration de la fonction dynamique de la colonne vertébrale.

Le développement d'un modèle n'est licite que si l'on possède une idée extrêmement précise de l'utilisation qui en sera faite : "It is unrealistic and counterproductive to hope for one "final" model to answer all practical questions". C'est en ces termes que s'explique H.E. von GIERKE dans son rapport d'évaluation technique en 1978 à propos des modèles et analogues utilisés pour l'étude de la réponse dynamique humaine (AGARD CP 253). L'auteur souligne en trois points qu'un certain nombre de conditions doivent toujours être respectées.

1) - Il est nécessaire que la réponse du modèle soit cohérente, d'une part avec les résultats d'expériences humaines conduites jusqu'à des niveaux sous-lésionnels (impact) et d'autre part avec les mesures d'impédance et de transmissibilité effectuées sur l'homme soumis à des vibrations dans une bande de fréquence digne d'intérêt.

2) - Les prévisions (du modèle) en matière de lésions - tant en ce qui concerne leur situation que leur gravité - doivent concorder avec :

* les lésions qui sont observées chez les personnes rescapées ou décédées après les accidents d'avions ou d'automobiles (les circonstances de l'accident et de survenue des lésions étant finement analysées),

* les résultats d'expériences (impacts horizontaux et verticaux) effectuées sur des cadavres utilisés pour compléter les données précédentes.

* attribuer aux coefficients du modèle les valeurs spécifiques du matériaux qu'il caractérise (raideur ou propriétés élastiques des corps vertébraux).

3) - Les résultats obtenus en utilisant des animaux d'expériences (réservés aux cas qui ne peuvent être étudiés par les méthodes précédentes - doivent obéir aux règles communément admises concernant le mécanisme des lésions, leur localisation et leur gravité.

On ne peut qu'être profondément d'accord avec les généralités qui viennent d'être énoncées. Leur application a fait preuve d'efficacité dans les dernières décennies, surtout lorsqu'elles s'exercent dans le domaine mécanique ou un signal d'excitation - choc ou vibration forcée - provoque dans la structure (ici le rachis) une réponse du même type i.e. une vibration transitoire ou entretenue.

Malheureusement, il est clair que la théorie du modèle atteint ses limites qand la réponse délivrée n'est plus strictement celle du système étudié, que de plus elle n'est pas quantifiable, et qu'enfin elle n'est pas du même type que l'excitation qui l'engendre. Ainsi l'exemple du choc appliqué sur la colonne vertébrale d'un lombalgique : le résultat est une douleur ; réponse sensorielle éminemment variable d'un individu à un autre, non quantifiable de façon objective, et pour laquelle les systèmes et appareils mis en jeu dépassent de très loin la seule colonne vertébrale.

Comment alors valider un modèle lorsque l'individu lombalgique qui ne présente aucune altération morphologique ou anatomique de sa colonne ne peut être examiné que sous l'angle statique ou cinématique (limitation ou altération de position ou de la géométrie des mouvements) ? Il manque une information essentielle, absolument nécessaire à la validation d'un modèle. Il manque l'information sur la fonction dynamique du rachis, celle-là même qui rend les mouvements du tronc possibles et harmonieux.

En observant les variations des paramètres mécaniques qui rendent compte de la dynamique du rachis on se donnerait la possibilité d'étudier sur la colonne une grandeur physique de même nature que le signal d'excitation. Dès lors qu'on accède à de tels paramètres, on se trouve ramené à un problème classique et il redevient licite de tenter de valider un modèle d'une part et de développer une exploration fonctionnelle du rachis chez l'homme.

La question ultime est alors : comment obtenir un paramètre dynamique, objectivement quantifiable sur la colonne vertébrale ?
Les propositions qui sont exposées à la fin de cet article ne relèvent encore que d'hypothèses. Certaines sont vérifiées, d'autres sont en voie de l'être et la radiographie éclair sera peut être le meilleur moyen de transposer à l'homme des méthodes de surveillance identiques à celles qui sont utilisées dans l'industrie et exposées ci-après.

L'ensemble ostéoligamento-musculaire de la colonne et des muscles paravertébraux présente des caractéristiques dynamiques spécifiques quand il est excité par un stimulus mécanique : l'identification des caractéristiques de l'organe peut être envisagé par "l'analyse de signature" qui n'est autre que son comportement en fréquence (en général le terme s'attache aux informations acoustiques et vibratoires, bien qu'il soit possible d'envisager l'analyse de la signature thermique ou celle relative à tout autre paramètre physique).

Au début il est indispensable de valider une signature de référence (rachis sain) à laquelle seront comparées les autres signatures recueillies en présence de troubles parfaitement étiquetés ; sciatique, lombalgie, syndromes des facettes, etc... A une altération fonctionnelle correspond une altération des fréquences. Nous proposons donc de surveiller la dynamique vertébrale par la même méthode d'analyse de signature utilisée par les industriels pour surveiller les machines tournantes ou vibrantes (CROS J.F., 1979 (5)).

Les exemples donnés sur les figures 11 à 13 n'ont aucune prétention à l'exactitude.

Ils n'ont qu'une valeur explicative. De même que le schéma de la figure 10 qui modélise trois vertèbres, deux disques et les muscles paravertébraux.

Chaque vertèbre correspond à une raideur élastique de valeur élevée, les muscles à des raideurs de valeurs faibles montées en parallèle. Les disques intervertébraux sont représentés par des raideurs et des amortisseurs parallèles.

La mise en place d'accéléromètres sur les corps vertébraux d'un primate a bien montré qu'il existe une fonction de transfert caractérisée par un module et une phase pour chaque disque intervertébral. On étudie ainsi le comportement en fréquence du complexe intervertébral sollicité par la propagation de l'onde vibratoire, qu'on appelle "signature" de l'unité saine.

Il est certain que cette signature sera différente si l'amortisseur discal ne remplit plus son rôle (déshydratation du nucleus pulposus). Différent également pour une paralysie flasque des muscles paravertébraux (disparition de la raideur parallèle), ou pour une rigidification de la colonne (spondylarthrite ankylosante).

La pathologie rhumatismale ou infectieuse modifie donc le comportement en fréquence du système. Les mouvements fins de la colonne étant altérés bien avant que n'apparaissent les signes radiologiques de la maladie, "l'étude de l'analyse de signature" de l'organe constituerait une véritable exploration paraclinique fonctionnelle de la colonne vertébrale.

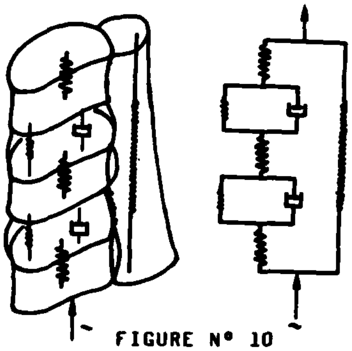


FIGURE N° 10
SCHEMA D'UN MONTAGE SERIE-PARALLELE COLONNE VERTEBRALE ET DES MUSCLES PARAVERTEBRAUX

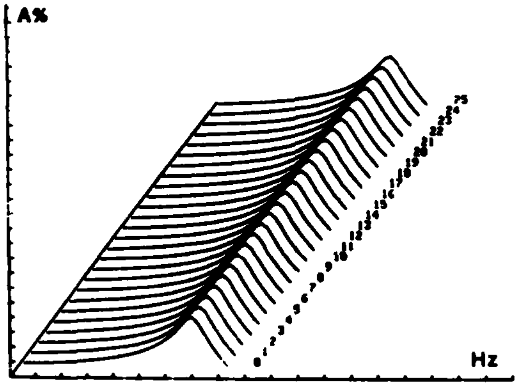


FIGURE N° 11
REPRESENTATION SCHEMATIQUE DE LA REPONSE DE LA COLONNE VERTEBRALE (les disques sont référencés de zéro à vingt-cinq).

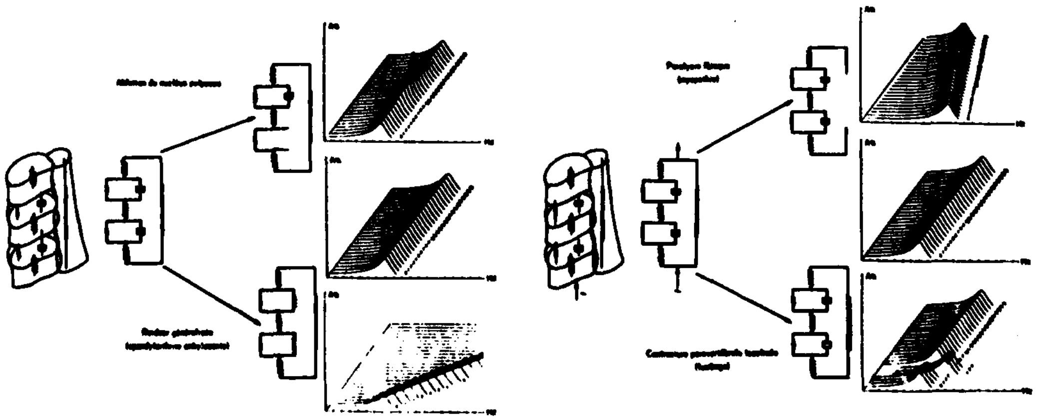
La figure 11 est une représentation hypothétique en trois dimensions de la réponse de la colonne vertébrale à une excitation sinusoïdale. En x les fréquences, en y le niveau des disques vertébraux repérés pour la clarté de l'exposé de 0 à 25, en z les amplitudes des fonctions de transfert de chaque disque en fonction de la fréquence.

Les figures 12 et 13 représentent les variations de signature auxquelles on peut s'attendre dans deux types de pathologie, musculaires et discales.

En cas de paralysie flasque (figure 12 haut) la disparition complète de la raideur musculaire à tendance à déplacer les fréquences de résonance vers les basses fréquences, ceci de façon globale. Une raideur paravertébrale localisée déplacerait au contraire les résonances des disques intéressés vers les hautes fréquences (figures 12 bas). Dans une atteinte discale (figure 13) la disparition de l'amortissement nucléaire entrainerait une augmentation d'amplitude du module de la fonction de transfert. Le blocage généralisé de la colonne vertébrale telle qu'il est réalisé dans la spondylarthrite ankylosante, devrait déporter l'ensemble des fréquences de résonance vers la droite par augmentation des coefficients de raideur discaux.

Une proposition qui vise à mettre au point un tel type d'analyse de signature sur la colonne vertébrale de l'homme est-elle réaliste ?

La volonté de pratiquer un examen à caractère non sanglant sur un organe profond oblige à envisager une exploration de type ultrasonore ou radiologique. Si la description suivante fait appel à l'imagerie radiologique, il n'est pas exclu qu'un tel examen puisse être réalisé par ultrasonographie grâce à l'amélioration de la résolution des images obtenues par cette dernière méthode en plein développement.



FIGURES N° 12 - 13

La réalisation d'une exploration fonctionnelle dynamique radiologique de la colonne vertébrale humaine imposerait trois types de servitude,

- acquisition (servitude technologique ; rapidité d'acquisition de l'image),
- servitude liée à la pathologie du malade examiné (sollicitation vibratoire douloureuse chez un lombalgique) et à la dose de rayonnement à appliquer,
- la dernière difficulté est en quelque sorte le corollaire de la précédente.

L'agression vibratoire imposée au malade devant être minimale, les mesures effectuées sur les radiographies doivent minimiser l'erreur au maximum, c'est-à-dire présenter une grande précision quant au mouvement relatif d'une vertèbre par rapport à l'autre.

. Les problèmes posés par la rapidité d'obtention des radiographies chez un sujet non immobile ne sont pas récents. Ainsi, la méthode de sollicitation vibratoire devant un appareillage radio a déjà été expérimenté en 1967 par WEISS et MOHR (49). Ces auteurs ont obtenu une image cinéradiographique du mouvement du diaphragme d'un sujet soumis à une excitation impulsionnelle.

. Si, dans cette étude les doses de rayonnement appliquées au sujet d'expérience ont été jugées raisonnables, il reste à définir l'amplitude de vibration supportable par un lombalgique en position assise par exemple. A l'évidence, ce paramètre ne peut être que de faible valeur et devra faire l'objet d'études préalables.

. L'utilisation de la radiographie éclair, règle le problème du temps de pose (10^{-8} s).

Par ailleurs, les erreurs de mesure (exprimées en degrés) sur la position relative de deux os adjacents entre deux positions différentes peuvent atteindre des valeurs importantes. BENSON et Coll. 1976 (1) montrent que l'ensemble des biais anatomiques physiologiques ou expérimentaux provoquent une incertitude de 50 % sur la connaissance d'une rotation de 30°" par exemple. Considérations coroborées par DRAN 1979 (10) et dont les raisons avaient été antérieurement définies par NASH et MOE dès 1969, (26).

Cependant, HANLEY et Coll., 1975 (12) obtiennent une précision de l'ordre du degré sur la détermination de la flexion extension de la colonne lombaire. DIMNET 1979 (7) et en collaboration avec PANJABI et al. en 1978 (30) obtient une précision de 0,3°" sur la mesure du déplacement relatif de deux vertèbres immobiles mais en position différente. Cette acquisition permet à PASQUET 1980 (31) d'étudier les paramètres descriptifs de la colonne vertébrale en radiographie de profil avec une grande précision.

Si donc l'acquisition et le traitement d'un signal d'imagerie en régime dynamique ne mettent plus de barrière insurmontable au développement d'un tel examen ; on peut espérer valider "une exploration en analyse de signature" en laboratoire et sur l'animal de la manière suivante :

un animal bioinstrumenté à l'aide d'accéléromètres miniatures sur la colonne est soumis à des vibrations, tandis que des radiographies sont pratiquées dans le même temps.

Deux types de signaux sont obtenus sur le rachis :

- des signaux électriques (accéléromètres)
- des images radiologiques.

Sur les films radiographiques, les techniques de reconnaissance de forme et de traitement d'image, ainsi que les calculs de centre instantané de rotation sont effectués. Les résultats de l'analyse harmonique pratiquée sur ces points seraient comparés au même traitement analytique des signaux objectifs (accéléromètres). Une bonne concordance des résultats validant la méthode chez l'animal permettrait d'envisager de façon réaliste une application à l'homme : l'exploration de la fonction dynamique de son rachis.

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DISCUSSION

PRIVITZER, US: I agree with your remarks regarding the difficulties in modelling the spine. Now I'm speaking of modelling in the mechanical sense, rather than in the statistical sense, for the purpose of predicting the experience of back pain or back discomfort -- that is, indeed, a very complicated problem. Another thing I want to point out is that the model described in AGARD Conference Proceedings Nos. 253 (pp. A9-1 to A9-15) and 322 (pp. 30-1 to 30-10) was not developed to predict back pain; but, rather, to predict the likelihood of vertebral compressional injury in impact environments, such as aircraft ejections or helicopter ground impacts. The model may also be used to establish optimal seat and restraint system configuration limitations on encumbering devices, masses and locations, and limitations on accelerations transmitted to the occupant through the seat. Most problems have not been associated with the modelling techniques; but, rather, with the considerable paucity of experimental data that are required by such a model. In other words, most of the simplifying assumptions that were made were required because of the lack of data, rather than any shortcomings of the analytical techniques.

QUANDIEU, FR: I'm in complete agreement with your comment. It is clear that "signature analysis", in that it is an application in biology of what is done in industry, is only applicable at low levels of force. Signature analyses which go to the point of destruction of the system under study are not directly interesting on the one hand; on the other hand, these would not be directly interesting in biology, because they would enter quickly into the non-linear portion of the system response.

RECHERCHE AUTOMATIQUE DE POSTURE OPTIMALE

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RESUME

Cette communication expose une nouvelle perspective en ergonomie de conception. Il y est présenté notamment une partie du travail réalisé dans ce sens, la recherche automatique de posture optimale pour un modèle humain, dans un environnement, défini ou non.

1 - INTRODUCTION -

La recherche automatique de posture optimale représente une première partie des recherches en cours au Laboratoire d'Anthropologie Appliquée, visant à réaliser un système intégré intelligent en ergonomie de conception. Un tel système représente une structure complexe, impliquant de multiples sous-ensembles ou modules possèdant entre-eux une grande indépendance de conception. Le modèle de recherche automatique de posture optimale est l'un des plus importants pour l'ergonome travaillant sur un projet car la méthode non automatisée de mise en posture est fastidieuse, et met en oeuvre des méthodes empiriques délicates à justifier. Une justification existe malgré tout puisqu'elle concerne la qualité du résultat. Elle est bien souvent suffisante au yeux de l'expert. Dans une approche différente, on peut espérer que tout le savoir-faire et les connaissances de cet expert puissent être formalisés, gérés par une structure informatique, puis réutilisé de façon automatique permettant ainsi de progresser dans l'optimisation des travaux d'ergonomie de conception.

2 - BASE DU TRAVAIL -

Une étude complète a été réalisée au sein du laboratoire, afin de créer un modèle de représentation de l'opérateur humain qui réponde à un certain nombre d'impératifs :

- simplicité,
- souplesse,
- réalisme.

Dans cette optique, le modèle suivant a été retenu : la description de l'individu repose sur une représentation sous forme de chaînons articulés et on ne retient, dans un premier temps qu'un nombre limité d'articulations et de degrés de liberté : soit huit articulations et des déplacements dans un plan sagittal (figure 1). Chaque segment est considéré comme linéaire, et chaque articulation est assimilée à un centre de rotation plan. Les segments sont les suivants : tête (en fait, on choisit une position d'oeil théorique), rachis cervical, rachis dorsal, rachis lombaire, rachis sacré, cuisse, jambe, et pied.

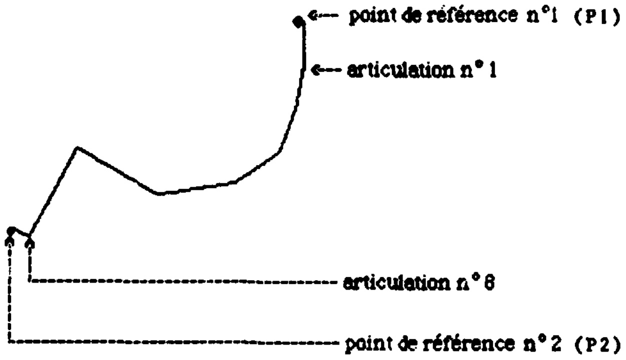

Figure 1

3 - PRINCIPE DE LA RECHERCHE -

L'objectif consiste à réaliser à partir d'un certain nombre de points de l'espace, la mise en posture d'un modèle du corps humain. Le contexte général de l'environnement est défini par différents sous-ensembles du système ERGODATA :

- un logiciel de C.A.O. (EUCLID),
- la banque de données de biométrie et de biomécanique,
- les références et fiches de synthèses en ergonomie.

Le programme présenté ici est indépendant du logiciel de C.A.O. utilisé. Les points, dits de référence, peuvent être définis en nombre quelconque. L'étude effectuée a montré que le nombre de points décrits par le chercheur est généralement inférieur à cinq, mais il aurait été dommage de limiter les possibilités du logiciel dès son analyse, aussi n'y-a-t-il aucune restriction sur ce point. Les points les plus fréquemment fournis par le chercheur sont la position de l'oeil, ou de l'appareil de visée, et la position du repose-pied (figure 1). Il est plus rare de voir définie la position de la hanche (trochanter). Mais il est clair qu'il peut être nécessaire de fournir des données autres que des points de référence, ou tout au moins complémentaires. Ainsi, il est fréquent de devoir définir des angulations précises, dues à des contraintes de conception. Il est donc possible de décrire pour une ou plusieurs articulations, la valeur de l'angulation, ou de l'intervalle d'angulation.

Tous ces points doivent naturellement être d'une parfaite cohérence pour permettre à l'algorithme de travailler correctement. Une erreur dans une valeur d'angulation peut entraîner un résultat entièrement faux, sans que cela soit décelé par le chercheur, le résultat semblant plausible.

4 - RECHERCHE DE LA POSTURE OPTIMALE -

4.1 - Modèle utilisé -

La Recherche de Posture Optimale est réalisée à l'aide d'un algorithme dit de PROGRAMMATION DYNAMIQUE.

- Description du procédé :

A chaque articulation sont affectées trois valeurs, ou ensembles de valeurs, numériques. Tout d'abord, une valeur de référence idéale, la valeur qui correspond à la meilleure angulation pour cette articulation. Puis, un ensemble qui représente l'intervalle des angulations acceptables, pour l'articulation. Enfin, un ensemble qui représente l'intervalle des valeurs d'angulations pour l'articulation. Ces valeurs ou ensembles seront notés :
. VRI : valeur de référence idéale,
. IE : intervalle ergonomique,
. IA : intervalle anatomique.

Pour ces "ensembles", on a évidemment la relation suivante :

$VRI \subset IE \subset IA$ ($\subset$ étant le symbole d'inclusion).

Pour IE et IA, on utilisera les notations suivantes ; e_i et E_i seront respectivement la borne inférieure, et la borne supérieure, de l'IE d'indice i. Il en sera fait de même avec l'IA, en utilisant les variables a_i et A_i.

4.2 - L'algorithme de programmation dynamique -

4.2.1 - Généralités :

A partir des ensembles décrits précédemment, un chemin est déterminé. Il doit donc prendre en considération les paramètres déterminés par l'expérimentateur, c'est-à-dire les n points de référence. Le meilleur chemin, au sens d'une fonction d'évaluation utilisée par l'algorithme, est celui optimisant cette fonction d'évaluation. Il est évident que la recherche d'un tel chemin, sans méthodes performantes, serait très longue, et très coûteuse en taille mémoire. En effet, la programmation dynamique permet d'éliminer, à chaque étape, la totalité des chemins non-optimaux, d'où un important gain de temps. Il faut de plus noter que l'algorithme est complet, c'est-à-dire que si un chemin optimal existe, l'algorithme est assuré de le trouver. L'élimination à chaque niveau peut se révéler néanmoins un sérieux handicap, car, des chemins non optimaux, donc éliminés, peuvent se révéler intéressants par la suite, ce qui occasionne, nous le verrons, une perte d'information.

4.2.2 - Description de l'algorithme :

Pour passer de l'articulation i à l'articulation i+1, on calcule le "coût" de chaque chemin de l'articulation i, avec l'angulation x_i, à l'articulation i+1, avec l'angulation x_{i+1} (figure 2). Puis pour chaque angle de i+1, on retient comme chemin optimal celui qui a l'évaluation la moins élevée (figure 3). Ainsi, à la dernière articulation, il est possible d'obtenir le meilleur chemin, qui est représenté par l'ensemble des angles ou des positions recherchés.

Figure 2

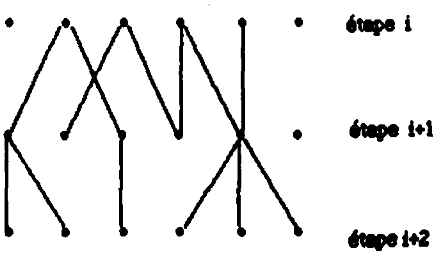

Figure 3

Le programme ainsi implémenté permet, avec pour toute connaissance fournie les points de références, de déterminer la meilleure position du sujet, la position la plus ergonomique.

5 - INCONVENIENT DU PROCEDE - AMELIORATION DE L'ALGORITHME -

5.1 - Limitations de l'algorithme de programmation dynamique -

Par cette méthode on définit la meilleure posture, compte-tenu des impératifs fournis en paramètres. Mais cette posture reste la meilleure d'un point de vue purement mathématique et même si le modèle est bon, cette optique très limitative peut s'avérer mauvaise. Supposons maintenant que, pour des motifs non mathématiques, la posture calculée ne soit pas acceptable ou ne soit pas ergonomiquement satisfaisante. Dans ces deux cas, il sera nécessaire de trouver une posture sous-optimale, et donc de modifier un peu la façon de voir les résultats. En effet, l'élimination, effectuée lors de chaque étape du traitement implique que des postures à peine moins bonnes, n'auront pas été considérées.

5.2 - Description de l'algorithme modifié -

Il est intéressant de stocker, non pas la meilleure posture, mais un certain nombre de meilleures postures. Cela a rendu nécessaire une analyse très approfondie du programme. Il est maintenant possible de retenir k postures, ce nombre k étant défini par l'utilisateur, en interactif, en début de programme. Pour cela un certain nombre de solutions est mémorisé à chaque noeud de l'arbre de recherche (figure 4), puis ces solutions sont traitées comme solutions globales à la demande du chercheur, non satisfait de la solution optimale détectée. Ceci permet donc de proposer une solution globalement satisfaisante, compte tenu de contraintes connues de l'ergonome, mais difficilement quantifiables dans le cadre d'un programme ou d'une expertise.

6 - DEVELOPPEMENTS DE LA METHODE -

Le premier développement est naturellement l'inclusion de données concernant les membres supérieurs, en particulier l'articulation très délicate qu'est l'épaule. Ce problème est actuellement à l'étude au laboratoire. Un premier travail a été réalisé, avec des paramètres simplifiés. Ceci a pour but de ne pas retarder l'exploitation en grandeur réelle du programme, en dépit de ce problème très sensible.

Cet algorithme pourra également être utilisé avec de plus nombreux paramètres. Ces paramètres pourront correspondre à un placement imposé (dans ce cas, d'autres points de référence en plus de P1 et de P2 pourront être fournis), ou pourront être des paramètres dynamiques, comme l'insertion des données concernant les mouvements des membres supérieurs, etc...

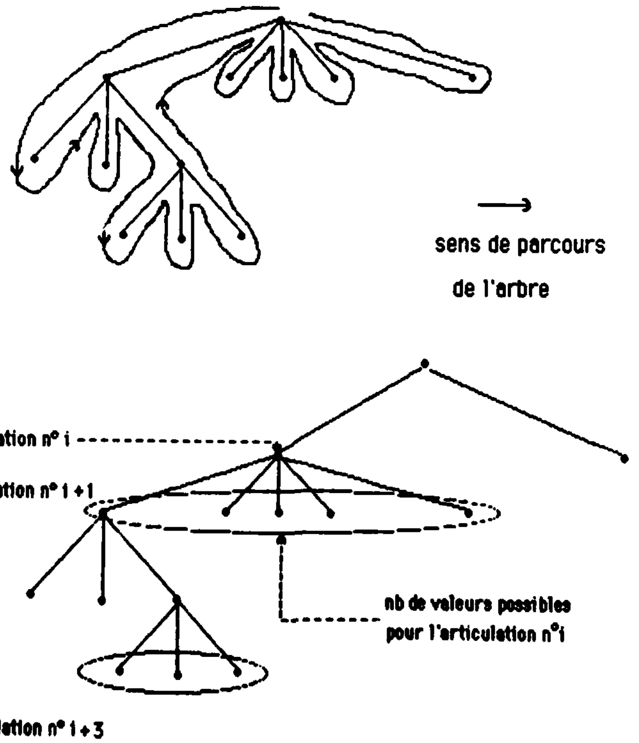

Figure 4

Pour cette raison, une troisième partie de l'étude est en cours, visant à introduire des notions de dynamique dans l'espace (augmentation du nombre de degrés de liberté). Elle porte actuellement sur l'étude du déplacement spatial du membre inférieur, ce membre semblant plus aisément modélisable. Lorsqu'elle aura abouti, il sera alors possible d'envisager une nouvelle extension, afin de prendre en compte les déplacements du membre supérieur. La richesse de l'information est, dans ce dernier cas, très grande, aussi l'étude doit porter non seulement sur les algorithmes tridimensionnels, mais aussi sur la structure des données à récupérer et à stocker.

7 - CONCLUSION -

Nous avons présenté ici un programme de mise en posture d'un modèle humain. Ce programme a été réalisé avec la volonté absolue d'être utilisable aussi bien seul, comme tout programme simple, qu'intégré à un ensemble de travail en ergonomie de conception. Ainsi, on peut dire que ce programme est le premier maillon d'une chaîne de travail intelligente, qui pourra réaliser un travail construit d'ergonomie, à partir d'une gestion des connaissances qui lui seront fournies. Cela fait partie de la volonté du **Laboratoire d'Anthropologie Appliquée**, d'utiliser des méthodes d'informatique de très haut niveau, et d'intelligence artificielle.

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ETUDE BIOSTEREOMETRIQUE DE LA COURBURE EXTERNE DU RACHIS POUR DIFFERENTES POSITIONS DE REFERENCE

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RESUME

Une analyse de la courbure externe du rachis a été réalisée à partir du relevé de données biostéréométriques, sur un groupe de sujets de sexe masculin, en position debout standard et pour différentes positions assises.

Les courbures externes du rachis ont été déterminées à partir des paramètres suivants : rayons de courbures dorsale et lombaire, positions des centres de courbures et localisation du point d'inflexion.

Les modifications des formes du contour externe ont ensuite été étudiées pour plusieurs positions assises. Les résultats de ces travaux sont utilisés pour la modélisation tridimensionnelle du corps humain et appliqués dans des analyses de postes en C.A.O. Ils peuvent également contribuer à une meilleure connaissance des relations entre les formes du dos en position fonctionnelle et les gênes ressenties pour des opérateurs assis.

1 - INTRODUCTION -

Les troubles qui affectent la colonne vertébrale constituent une préoccupation permanente des services de santé ainsi que des ingénieurs ergonomes qui doivent impérativement minimiser les contraintes de posture dans la création de nouveaux équipements.

Parmi les nombreuses causes de douleurs lombaires ou dorsales, les plus fréquentes demeurent liées :
- au transport de charges, qui, dans certains cas, agissent sur les disques intervertébraux provoquant des lombalgies aigües,
- à une position assise inconfortable de longue durée conduisant à une contraction des muscles du dos, difficilement supportable.

Si la connaissance des caractéristiques biomécaniques du rachis permet de mieux appréhender les causes d'accidents, liés au soulèvement de charges et de les prévenir par des recommandations simples, par contre, la résolution des problèmes de posture assise nécessite une meilleure connaissance de la variabilité interindividuelle de la forme de la courbure du rachis, tant en position debout standard, qu'en positions assise redressée et assise relâchée.

De nombreuses études portant sur les aspects biomécaniques du rachis et plus particulièrement sur la classification des types rachidiens ont été réalisées. BOUNACK (1941) a défini quatre catégories de courbures sur le vivant : dos droit, voûté, lordotique et cyphotique. En 1950, DELMAS a déterminé un indice de courbure rachidienne sur le squelette : $I = 100 \times \frac{h}{s}$ où h est la hauteur du rachis et s sa longueur. Il définit ainsi trois types de courbures à partir d'un découpage de l'indice suivant les valeurs : élevées de 96 à 100; intermédiaires de 94,1 à 96 et basses ou faibles de 94 et au-dessous. BROWN et Coll. (1976) ont étudié, à partir d'une méthode radiographique, l'orientation géométrique des vertèbres dans l'espace à 3 dimensions, obtenue par la coïncidence de deux plans. Les orientations ont été calculées à partir des angles d'EULER et les résultats confirment d'après les auteurs, les données de la littérature. SMIGIELSKA et Coll. (1981) ont pour leur part analysé les déformations rachidiennes des judokas sur des images de rachis obtenues en projection sagittale par mesure directe. En 1981, KNUSSMANN et Coll. ont utilisé une méthode photographique pour comparer les profils des rachis externes chez des sujets des deux sexes. En 1983, WIELKI et Coll. ont établi une classification des courbures du rachis à partir du relevé, par mesure directe, de points anatomiques entre C7 et L5 sur un échantillon de 170 femmes étudiantes en éducation physique. Les auteurs déterminent dans un plan sagittal, le rapport de deux cordes joignant les extrémités du rachis et qui passent par le point d'inflexion. Ils aboutissent ainsi à trois typologies de courbure : 82% des sujets possèdent une courbure normale, 8% sont lordotiques, avec un relèvement du point d'inflexion et 10% sont cyphotiques avec un abaissement du point d'inflexion. BRANTON (1984) a retenu la méthode radiographique pour reconstruire la courbure du rachis sur un échantillon de 114 sujets des deux sexes en position assise redressée. L'auteur détermine 5 points de repères compris entre le vertex et le sacrum et calcule le pourcentage de sujets lordotiques, à colonne raide et cyphotiques. De plus, il précise, à l'aide de son échantillon, les positions moyennes et écarts-types des points de référence qui lui ont permis de reconstituer le rachis dans un plan sagittal.

D'une façon générale, les études antérieures montrent que la classification des types rachidiens, sur le squelette comme sur le vivant aboutit à trois typologies distinctes. Toutefois, ils nous a paru intéressant d'analyser les modifications de ces typologies lorsque les sujets passent d'une position de référence debout standard à une position assise redressée puis à une position naturelle, assise relâchée. Dans cette perspective, une première étude a été effectuée à partir de mesures stéréométriques directes dans un anthropostéréomètre sur un groupe de sujets des deux sexes en position debout standard (PINEAU et Coll., 1983). En utilisant une méthode algébrique appropriée, nous avons calculé les paramètres décrivant les courbures dorsales et lombaires et défini ainsi trois types de courbure externe qui confirment les résultats des travaux de DELMAS (1950) effectués sur le squelette. En retenant la même méthode, nous avons réalisé une étude comparative portant sur la modification des paramètres algébriques décrivant la forme du rachis dans le passage de la position debout standard aux positions assise redressée et assise relâchée.

2 - METHODE -

2.1 - Technique de mesure -

Pour cette étude nous avons relevé les coordonnées tridimensionnelles de 15 points cutanés placés sur le contour externe du rachis entre C7 et L5 à l'aide d'un système de mesure indirecte, utilisant des caméras vidéo reliées à un mini-ordinateur (VICON, Oxford Metrics). Cette technique de mesure présente le double avantage d'être beaucoup plus rapide et précise dans la saisie de l'information que le système de mesure biostéréométrique directe. Les relevés ont porté sur un groupe de 9 sujets du sexe masculin pour les trois positions : debout standard, assise redressée et assise relâchée, soit 27 courbures externes. Le traitement des données est efffectué en utilisant la méthode algébrique décrite précédemment (PINEAU et Coll., 1983). Les courbures externes sont éditées en pourcentage de la hauteur du rachis (C7-L5) pour chacune des positions étudiées (figure 1).

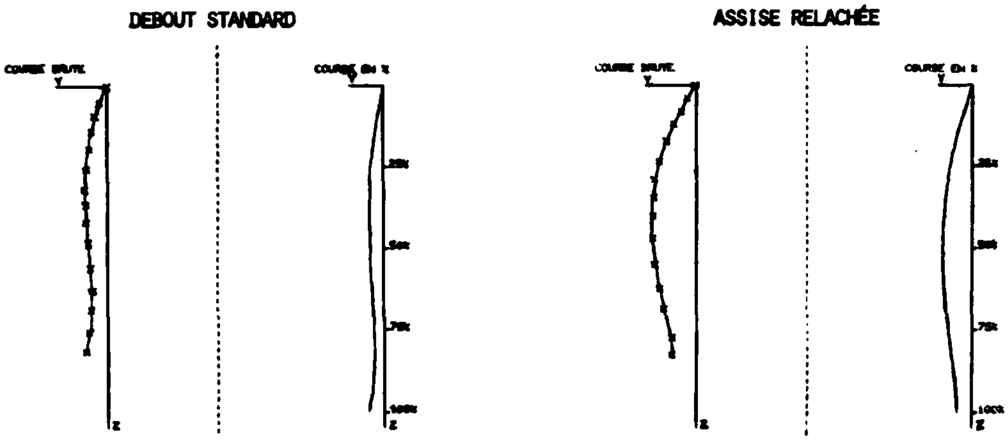

Figure 1 - Ajustement des valeurs expérimentales à partir d'une expression algébrique du 4ème degré. Exemple d'édition graphique pour deux positions - Plan sagittal vertical -

2.2 - Etude analytique -

Pour les différentes positions retenues, nous avons calculé les principaux paramètres algébriques décrivant la courbure externe du rachis : l'indice de courbure, la position du point d'inflexion, l'angle que fait la tangente à la courbe au point d'inflexion, la position des sommets et des rayons de courbures (figure 2).

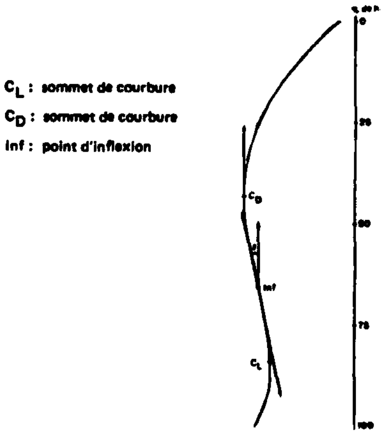

Figure 2 - Courbure externe du rachis obtenue par une équation du 4ème degré. (D'après PINEAU et Coll., 1983).

3 - RESULTATS -

Les variations interindividuelles des principaux paramètres algébriques décrivant la courbure externe du rachis pour les trois positions retenues : debout standard, assise redressée et assis relâchée sont reportées dans le tableau ci-après. Les valeurs sont exprimées en pourcentage de la hauteur du rachis (C7-L5) ce qui permet d'effectuer des comparaisons entre les sujets. Les coordonnées Z et Y du point d'inflexion et des sommets de courbures dorsale et lombaire représentent respectivement les cotes verticale et antéro-postérieure de la projection de la courbure du rachis dans un plan sagittal médian.

POSITIONS PARAMETRES	DEBOUT STANDARD	ASSISE REDRESSEE	ASSISE RELACHEE
Indice de courbure I	$95,5 < I < 98,8$	$96,4 < I < 99,4$	$91,5 < I < 96,1$
Point d'inflexion (Z,Y)	$50,5 < Z < 70,0$ $-2,1 < Y < 8,8$	$44,4 < Z < 65,8$ $-2,9 < Y < 11,0$	$70,0 < Z < 98,0$ $9,0 < Y < 17,0$
Angle θ (point d'inflexion/axe vertical) ..	$6,0 < \theta < 18,0$	$2,0 < \theta < 14,0$	$4,0 < \theta < 20,0$
Sommet de courbure dorsale (Z,Y) C_D	$23,3 < Z < 40,0$ $3,3 < Y < 14,0$	$19,0 < Z < 41,0$ $3,0 < Y < 11,6$	$48,0 < Z < 73,8$ $15,0 < Y < 28,0$
Rayon de courbure dorsale R_D	$55,0 < R_D < 138,0$	$55,0 < R_D < 170,0$	$62,0 < R_D < 175,0$
Sommet de courbure lombaire (Z,Y) C_L	$74,8 < Z < 93,0$ $-6,5 < Y < 5,0$	$71,0 < Z < 91,0$ $-7,0 < Y < 10,5$	$96,8 < Z < 99,9$ $6,0 < Y < 23,0$
Rayon de courbure lombaire R_L	$49,0 < R_L < 87,0$	$55,0 < R_L < 236,0$	$40,0 < R_L < 298,0$

Z : sens vertical (de C7 à L5 en positif). Y : sens antéro-postérieur (positif en arrière du sujet). Variation interindividuelle des paramètres algébriques décrivant la courbure externe du rachis dans 3 positions distinctes. Les coordonnées Z et Y sont exprimées en pourcentage de la hauteur du rachis (C7-L5) et θ en degrés.

Compte-tenu des résultats donnés dans le tableau ci-dessus et de la connaissance des valeurs individuelles théoriques décrivant les courbures externes des sujets pour les trois configurations retenues, nous avons effectué une analyse comparative des paramètres algébriques entre la position debout standard et assise redressée puis entre la position assise redressée et assise relâchée.

4 - DISCUSSION -

4.1 - Comparaison des courbures rachidiennes pour les positions debout standard et assise redressée

D'une façon générale, l'indice de courbure $I = 100 \times \frac{\text{hauteur du rachis}}{\text{longueur du rachis}}$ correspondant à la position assise redressée demeure supérieur à celui correspondant à la position debout standard. Cette modification de la courbure reflète la rectitude de la colonne liée à la bascule du bassin lors du passage à la position assise.

Si l'on observe effectivement une modification de la forme de la courbure entre la position debout standard et assise redressée, on constate toutefois que les principaux paramètres algébriques ne changent pratiquement pas. De plus, il existe une relation linéaire étroite ($r = 0,95$) entre les valeurs théoriques des deux courbures. Sur la figure 3, nous avons reporté les variations de la forme des courbures externes de trois sujets qui présentent des courbures externes très différentes. En particulier, on peut observer le déplacement des points caractéristiques - point d'inflexion et sommets de courbures - de part et d'autre de l'axe vertical pour les positions debout standard et assise redressée. Les amplitudes de variation des points caractéristiques indiqués dans le tableau montre que dans certains cas, le sommet de courbure lombaire et la position du point d'inflexion présentent des variations négatives dans le sens antéro-postérieur, la courbure coupant l'axe vertical.

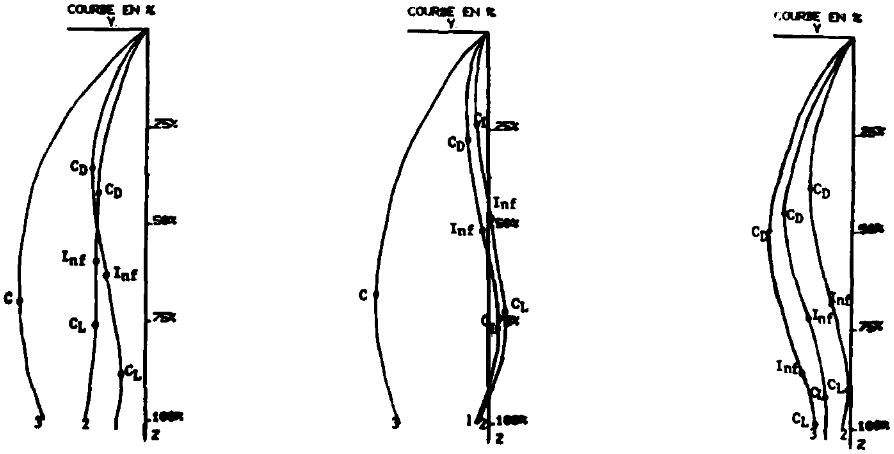

Figure 3 - Représentation dans un plan sagittal des courbures rachidiennes de trois sujets dans les positions : debout standard (1), assise-redressée (2) et assise-relâchée (3).

On observe que la variabilité interindividuelle la plus grande concerne les rayons de courbures dorsale et lombaire dont les valeurs sont comprises entre 30 et 240% de la hauteur du rachis. Par contre, les positions du point d'inflexion et des sommets de courbures dorsale (C_D) et lombaire (C_L) présentent une amplitude de variation plus réduite : 44 à 66% pour le point d'inflexion, 19 à 71% pour C_D, 70 à 93% pour C_L.

4.2 - Comparaison des courbures rachidiennes pour les positions assise redressée et assise relâchée

Le modèle algébrique utilisé pour décrire les deux premières positions s'applique également pour la position assise relâchée car on retrouve une corrélation très forte ($r = 0,95$) entre les valeurs observées et théoriques.

Pour la position assise relâchée, on observe que la colonne vertébrale accuse une forte courbure dans la partie médiane et dans la plupart des cas (7 sur 9 sujets) une faible courbure lombaire.

D'autre part, on constate qu'il n'existe pas de modification linéaire des paramètres algébriques dans le passage de la position assis redressée à la position assise relâchée. Il apparaît que les changements de courbure demeurent très variables suivant les sujets et cela quelque soit le type de courbures. Toutefois, l'expression algébrique permet de comparer les variations des coordonnées des sommets de courbures entre ces deux positions (cf. tableau ci-avant).

On observe :

- une diminution sensible de la cote verticale du sommet de courbure dont les variations passent de 19-41% à 48-74%,
- une augmentation dans le sens positif de la cote antéro-postérieure du sommet de courbure dont les variations passent de 3-14% à 15-28%.

Pour expliciter ces variations, nous avons reporté sur la figure 4 les zones de variations des sommets de courbures dorsale et lombaire pour les trois positions étudiées.

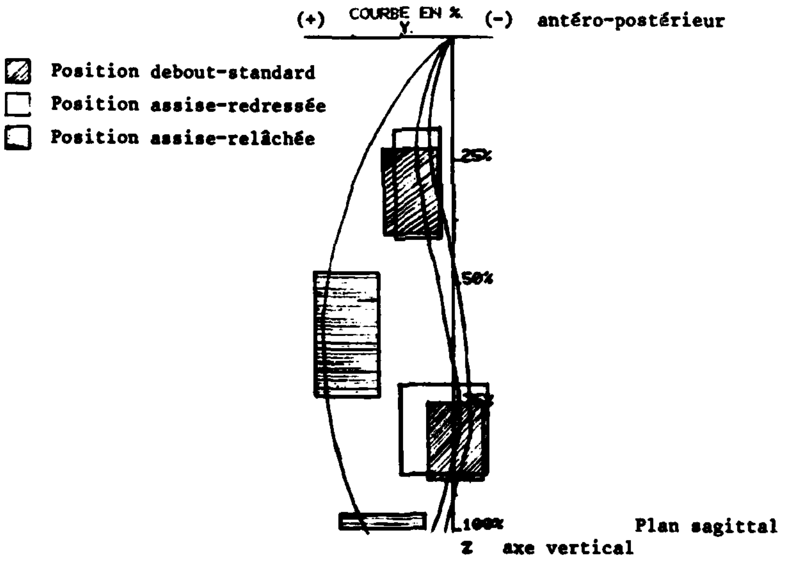

Figure 4 - Variations interindividuelles des sommets de courbures dorsale et lombaire pour 3 positions retenues.

5 - CONCLUSION -

Afin d'analyser les variations de forme du rachis lors de modifications de postures, nous avons réalisé une modélisation de la colonne vertébrale dans un plan sagittal et ainsi déterminé la variabilité interindividuelle des principaux paramètres décrivant la forme de la courbure. On constate que s'il existe une relation linéaire dans le passage debout standard à la position assise redressée, par contre, cette relation n'existe plus dans le passage de la position assise redressée à une position assise relâchée. Toutefois, nous connaissons les modifications de la forme de la courbure externe et en particulier les variations de la position des sommets de courbure. Ceci nous paraît constituer une approche précise pour les problèmes d'ergonomie, notamment pour la modélisation tridimensionnelle du corps humain et les études de conception de poste d'activité par C.A.O.

Nous envisageons maintenant d'appliquer cette méthode à un échantillon plus important, comprenant des sujets des deux sexes afin d'étudier les formes de courbures du dos en position fonctionnelle (assise relâchée) en relation avec les gênes ressenties.

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INVESTIGATION OF THE LUMBAR FLEXION OF OFFICE WORKERS

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SUMMARY

Modern furniture in schools, factories and offices is constructed in such a way that no one can use it properly. Each day people sit for many hours hunched over their tables in postures extremely harmful to the back.

A considerably better sitting posture can be obtained if the table is constructed higher and if it is tilted about 10°. In this way a book or item is brought closer and is at a better angle to the eye. The worst bending of the neck is thus avoided. Furthermore, the seat can, with advantage, be tilted 20° forward to reduce the flexion of the lumbar region. By both these means the extra 30° flexion, which is the most strenuous part of the flexion, is avoided. This can be demonstrated by means of an automatic camera. To control the flexion of various parts of the body, well defined anatomical points were marked on the skin or on the clothes.

INTRODUCTION

Almost half the population of the industrialised world is thought to be suffering from some form of back complaint. Apparently there is a general agreement, that straining of the back is an essential factor in provoking backache (Grandjean 1984). Kroemer (1971) states that "flattening or reversing the lordosis of the lumbar part can be especially dangerous".

In my opinion nothing will give as long lasting strain as the fact that most of us spend a good deal of our lives in a seated posture with flexed back.

THE RIGHT-ANGLED, UPRIGHT POSTURE

During the last 30-40 years there have been attempts to improve the seated work position for all age levels by replacing old furniture with newer types of tables and chairs. The socalled upright, right-angled position - viz, with the joints of the hip, knee and ankle at right angles - has for unknown reasons been considered the correct position.

Above all the lumbar support has been considered to be the means to improve the seated posture (Åkerblom 1948). But this is rather illogical as the lumbar support only carries about 5% of the body weight - and only in the reclined posture (Branton 1969). In the forward bent posture, in which most precision work is done, there is hardly any effect of the lumbar support. Moreover, when sitting reclined on a 5° backward sloping seat, you will have to bend even more in your neck to get into visual contact with items lying on the table. Consequently office workers today have more complaints from the neck and shoulder, than from the lumbar region.

No one has given any real explanation as to why this right-angled posture should be better than any other posture. Nevertheless, it has quite uncritically been accepted by experts all over the world as the only correct one. Very little interest has been attached to the seat, which carries about 80-95% of the body weight. Its influence on the posture of the body therefore must be more important.

CONCEPTS OF CORRECT SITTING POSTURE

There is world-wide unanimity of opinion with respect to "correct" sitting posture, namely that the body should be upright and the back straight. However nobody is able to sit in this posture while working.

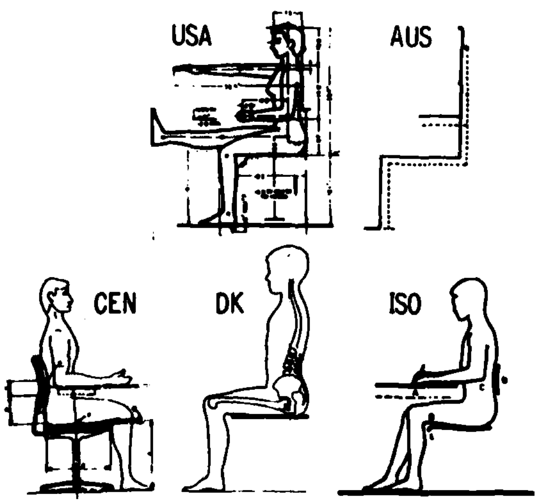

Fig.1: Schematic models representing "correct right-angled posture"

Sketches representing models for sitting postures from several countries are presented in fig. 1. These sketches constitute the basis of:

1) Anthropometry (Oxford, 1968: AUS)
2) International Standardisation (1978: ISO and 1979: CEN)
3) Training of designers (Dreyfuss, 1955: USA)
4) Training of people to sit "correctly" (Snorrason, 1968: DK).

It is surprising that no explanation appears to have been given substantiating why one should sit in this particular manner, nor is information supplied regarding the method by which the sketches were constructed. The Danish sketch (DK) may be the most interesting of them all. It clearly recommends that one should sit with a 90° flexion of the hip joint and a concavity in the small of the back. As I will try to demonstrate later, no normal person is able to sit in this posture while working. This sketch has simply depicted a skeleton sitting on a chair. The sitting posture of a skeleton, however, is not helpful in solving the problems encountered by persons. If preventive procedures were founded on such an insubstantial basis, the outcome would be doomed to failure.

POSTURE TRAINING

In Scandinavia enormous efforts have been made to teach people in schools, offices and factories better sitting postures - hoping that this will prevent the increase in the number of backsufferers. In fact we have tried to adjust the people to the furniture, and this is absurd. This instruction has mainly been given by the physiotherapists, and it might be of interest to see how they themselves sit while working.

Fig. 2 shows photos taken with 24 minute intervals by an automatic camera (ROBOT) during the final examination of physiotherapist students in Copenhagen. Most of them sit with pronounced flexion of the backs in postures, which have nothing to do with the upright one in the instructions.

Fig.2: Danish physiotherapy students during a four-hourly final examination.

ANATOMY OF THE SEATED PERSON

The conformation of a seated person has been unknown to most doctors, furniture designers, and physiotherapists; however the German orthopaedic surgeon, Hanns Schoberth, has carried out some excellent research on problems of sitting posture (Schoberth, 1962). The diagrams in fig. 3 were taken from his book.

When standing (A) there is almost a vertical axis through the thigh and the pelvis, and a concavity, or lordosis, is present in the small of the back. When a person is seated (B) the thigh is horizontal, the hip joint is flexed by about 60° and the pelvis has a sloping axis. The lumbar region then exhibits a convexity, or kyphosis. Schoberth found in X-ray examinations of 25 persons seated upright an average flexion of 60° in the hip joint and a 30° flexion in the lumbar region. Even in the ordinary relaxed position there is considerable loading. If it is necessary to bend further forward, such as most people do when reading, writing or drawing, most of the movement will also mainly take place in the 4th and 5th lumbar discs, which are thus additionally loaded. In the whole of the breast region of the spine there is practically no movement since the ribs give stability.

When stooping, the front edges of the lumbar vertebrae are pressed towards each other with considerable force (50-150 kg). Thus, the lumbar vertebrae press the discs back towards the spine while the rear edge of the vertebrae are pulled apart with a corresponding force. Chronic back pains are often localised in the lower lumbar region and sufferers characteristically find they cannot sit in an upright position for any length of time. Even for a healthy back a 30° flexion seems to be the maximum load the back can take for longer periods (Keegan 1953).

Åkerblom (1948) found an average flexion of 35° in the lumbar region of 20 persons sitting upright.

The American orthopaedic surgeon, J.J. Keegan (1953), took X-ray photographs of individuals lying on their sides (fig. 4). He considered a posture of about 45° flexion of the hip (c) to be normal, because this is the position one assumes when lying relaxed on one's side. In this conformation there is complete balance between the muscles at the front and back of the pelvis. When standing (a and b) the muscles in front become more tense and at the back they become more relaxed. This results in an increased lordosis in the lumbar region. When sitting (d and e) the muscles at the back are more tense and those in front are more relaxed; the small of the back is normally convex, i.e. it displays kyphosis, which is due partly to the tense hamstring muscles in the sitting position. The conformation illustrated in (e) is very nearly the posture adopted by seated school children for many hours each day.

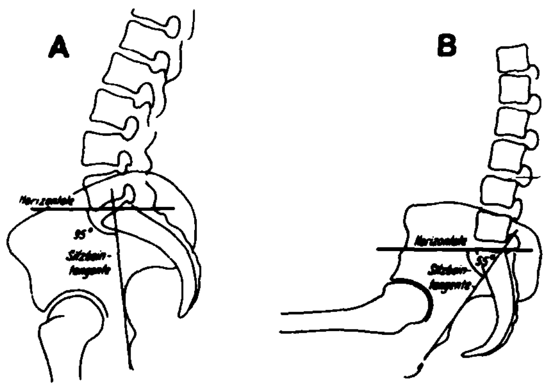

Fig.3: Normal anatomy of the lumbar region,standing A and sitting B (from Schoberth 1962)

When sitting on the back of a horse, one is very nearly able to assume Keegans "normal" posture (c), as the thighs are elevated by about 30°. When the hip joint has a flexion of 60°, one can sit upright with a vertical pelvis without bending the lumbar region (fig. 5).

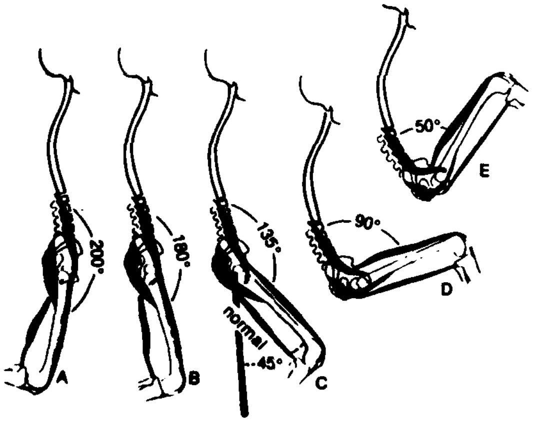

Fig.4: X-ray photographs of an individual lying on his side (from Keegan 1953).

Most children instinctively tilt forward in their chairs when reading and writing at a table (fig. 6). They obviously feel more comfortable in this position, and they are able to sit with a straight back. With an elevation of 30° in the thighs and a flexion of 60° in the hip joints, they only have to bend about 10° in the lumbar region to obtain an eye distance of about 30 cm from the book. Parental training, however, has forced children to give up this practice.

NEW EUROPEAN STANDARDS ARE HARMFUL TO THE BACK

During the last century the average height of man has increased about 10 cm and in the same period the height of the tables has for some incomprehensible reason been reduced by almost 10 cm. Since the visual distance has remained the same - for grown ups about 30-40 cm - lower tables will inevitably lead to a more constrained posture. It seems obvious that higher furniture is necessary to obtain a sitting position with sloping thighs and preserved lordosis as you will find it in the "Keegan normal position" and in the horse rider.

In 1982 The European Standardization for Office Furniture, CEN, has suggested that all non-adjustable tables should be of 72 cm height. No explanation for the advantage of these very low heights were given, except that it was "to achieve good postures". No names were given of the persons responsible for these draft standards. The influence on the posture of these low standards have never been controlled. All is based on aestetical, moral, technical and economical considerations.

A few years ago I investigated which height of furniture the consumers themselves wanted (Mandal, 1982). 80 persons were asked, and almost all preferred to sit about 15-20 cm higher than the mentioned standards, provided that the seat and the desk were sloping towards each other. In the higher position they felt less discomfort or pain in the back and they were all sitting with a much straighter back.

Fig.5 & 6: When sitting on horseback or when tilting forward on the chair the lordosis is easily sustained.

A. LABORATORY EXPERIMENT

To evaluate the effect of the furniture height on the flexion of the back (hip joint and lumbar region) a person (of 171 cm height) was asked to sit and read in a chair with 5° backwards sloping seat of 43 cm height and a table of 72 cm with a horizontal desk as advocated by CEN (fig. 7A).

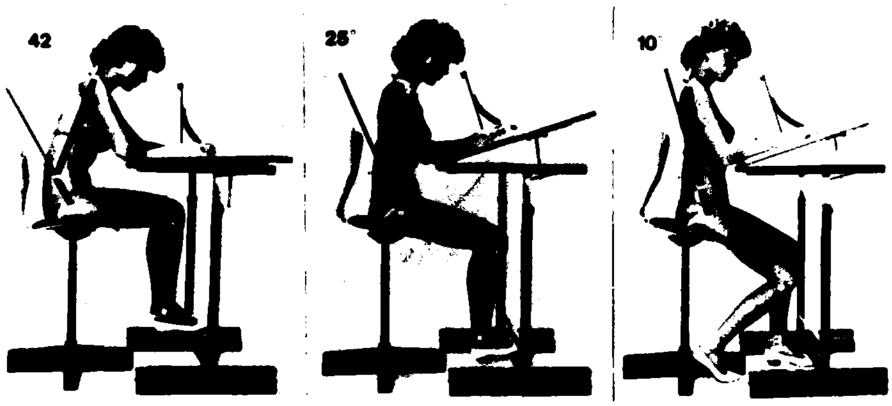

Fig.7: A-table height 72cm CEN standard B-table height 82 C-table height 92cm Preferred height

The feet were supported by a transverse bar under the table 20 cm above ground level (to achieve the desired table height of 72 cm), and for 20 minutes the girl sat reading at table height 72 cm/chair 43 cm. During this period 5 pictures were taken with 4 minute intervals by an automatic camera (fig. 7A). For the next 20 minutes she remained seated at a table height of 82 cm (achieved by placing the feet on a transverse bar 10 cm above ground level) chair height now 53 cm. The desk and the seat sloped 15° towards one another (fig. 7B). In this position 5 photos were also taken with 4 minute intervals. Finally the girl was asked to place her feet on the floor to achieve a table height of 92 cm, measured at nearest edge (fig. 7C) - chair height 63 cm, measured at axis of rotation. In all three situations she was asked to sit in the position she found most comfortable. No instructions were given concerning body posture or eye distance. The same experiment, using 3 table heights, was repeated for 10 days.

To control the flexion of various parts of the body, well defined anatomical points were marked with spots on the skin: 1) knee-joint (capitulum fibulae) 2) hip-joint (trochanter major) 3) 4th lumbar disc (a point midway between spina iliaca sup. anterior and posterior) 4) shoulder joint (acromion).

RESULTS

At the end of the experiment 50 photos of each of the 3 situations were available. The skin marks were connected with lines on the pictures. The resulting angles between these lines (hip angle, lumbar angle) were measured. The flexion of the lumbar region was found to be an average of:

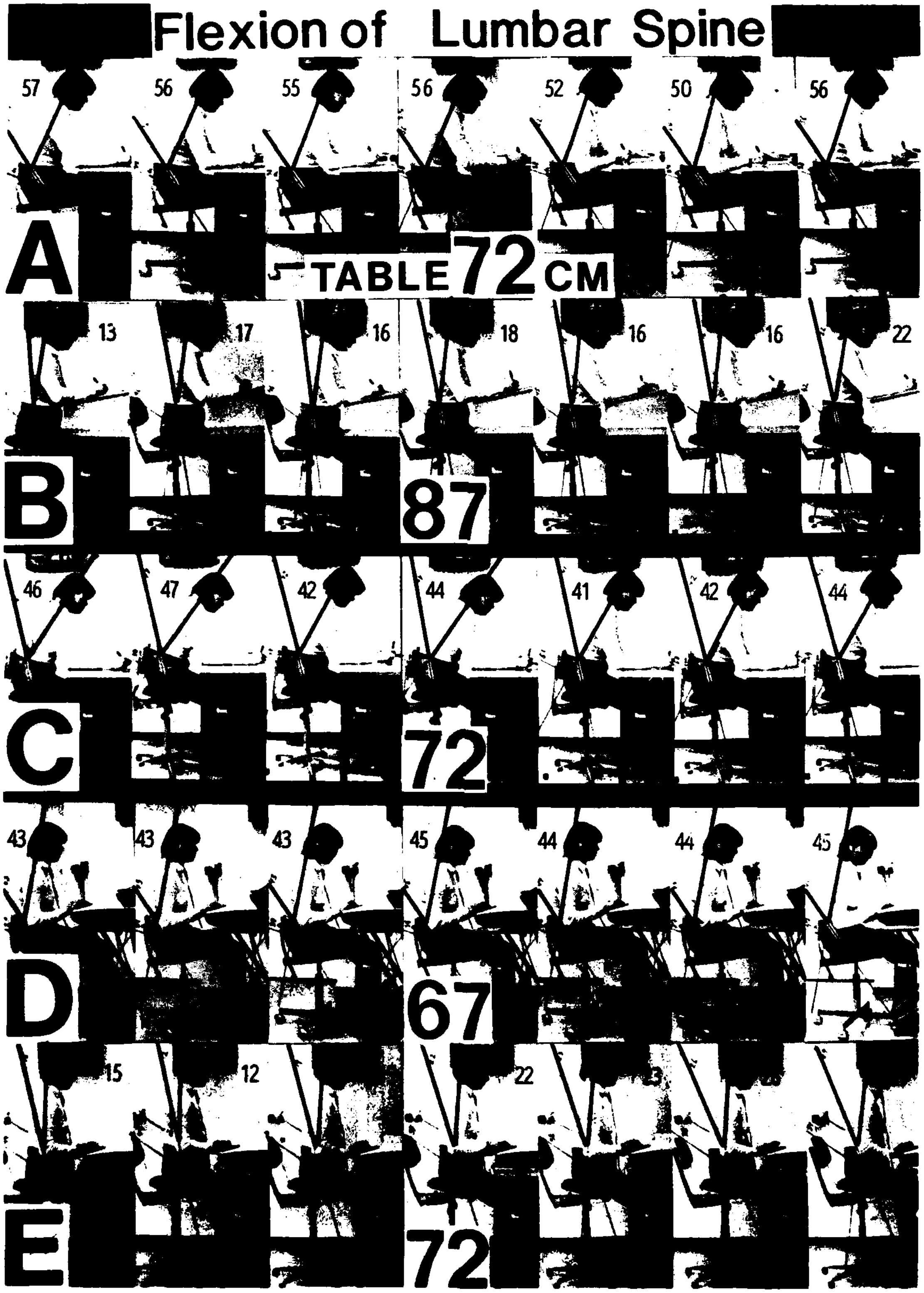

Fig.8: Workpostures with european standard height compared to the preferred height.

A: 42° at table height 72 cm
B: 25° at table height 82 cm
C: 10° at table height 92 cm

The flexion in the hip joint was found to be:

A: 57° at table height 72 cm
B: 50° at table height 82 cm
C: 42° at table height 92 cm

The variations are of course highly significant ($P<0.00001$).

In all the reduction of flexion in the lumbar region is 32° and in the hip joint 15°. This means that the total flexion of the back can be reduced by 47° by increasing the height of the table and chair by 20 cm, providing the seat and table top slope about 15° towards one another.

Finally the neck-angle was reduced from 69° in A to 56° in B and 49° in C.

The first day she preferred table height 82 cm. The following 9 days she definitely preferred table height 92 cm. The disc pressure will naturally be very low in this half standing position with preserved lordosis (Andersson 1974).

B. OFFICE EXPERIMENT

Conclusions from a laboratory experiment like the above mentioned should always be considered with some reservation as the person is away from her usual surroundings and this may affect the working posture. A more realistic view of posture can of course be obtained if you can examine people in their daily work. But problems with registrations of various postures and angles have so far made this difficult.

To try to overcome this problem I have marked the same anatomical points as mentioned above by marks fixed to the clothes. The persons were asked to use medium tight jeans and one end of a 13 cm long white nylon ruler was stitched to a point just outside the hip joint. The other end of the ruler was stitched to the jeans at a point outside 4th lumbar disc. In this way the axis of the pelvis and the hip joint was marked (fig. 8). Besides the shoulder joint being marked by a white tape and the knee joint marked by a cirkular bandage (velcro), both were marked with a small black spot for measuring.

For this experiment all 10 secretaries from the Dept.s. of Surgery and Plastic Surgery, Finsen Institute, were used. Height limits were 160 to 178 cm. Three different situations were examined.

A:Read/write	table 72 cm -5° chair 49 cm	(CEN recommend.)
B: Read/write	table 87 cm tilt-chair 59 cm	(Mandal recommend.)
C: Read/write	table 72 cm tilt-chair 51 cm	(Bendix recommend.)

The three different sitting postures were maintained for 15 minutes each. During this period the person was left alone in the office. She was instructed to sit the way she found most comfortable and asked to concentrate on the work. The pictures were taken with two minute intervals resulting in 7 pictures of each situation. The average lumbar flexion was reduced by 17.1° when changing from European Standard furniture (fig. 8A) to a 15 cm higher workplace with tilting chair and sloping desk (fig. 8B). Besides the flexion of the hip joint was reduced by 7.1°. This means that the flexion of the back (hip joint plus lumbar region) was reduced by 24,2°.

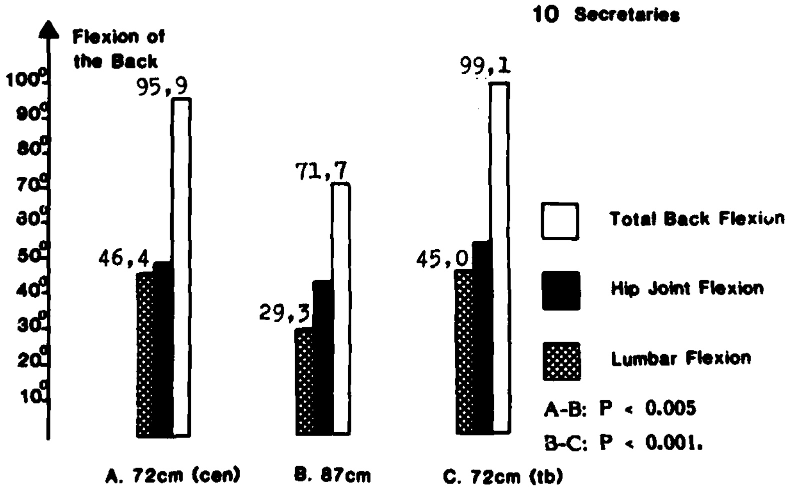

Fig.9 Flexion of the back.

By a similar experiment with typewriting I found an average reduction of backflexion of 9.2° when the CEN furniture (table height 67 cm) was substituted by table height 72 cm and a higher tilting chair (Fig. 9 D+E).

At the end of each test the pressure on the feet was measured by installing a bath room scale under the feet. The pressure was found to be 21% of the bodyweight in A compared to 27% in B. This is a rather modest increase compared to the fact that 100% of the bodyweight is on the feet when standing (fig. 10).

In Scandinavia there have within the last few years been attemts to use the tilting chair in a new way. T. Bendix (1983) preferred a distance of 21 cm between tabletop and center of the seat and positioned the persons entirely back on the rear part of the seat (fig. 8C). When the seat tilted forward, the distance, however, was reduced to 16-17 cm. When the tilting chairs were used in this way, I found an average decrease of the lumbar flexion of 1.4° compared to the CEN chair and an increase of 15.7° compared to the tilting chair with tall table (fig. 8B). Tom Bendix himself found a reduction of lumbar flexion of 0,8° when using a 5° forward sloping seat. The comfort estimation of the T.B. position was 1.0 (1=miserable). The persons estimated the tilting chair with tall table to a comfort rate of 4.6 (5=excellent). The comfort estimation of the CEN height was 2.0. P<0.001 (A-B).

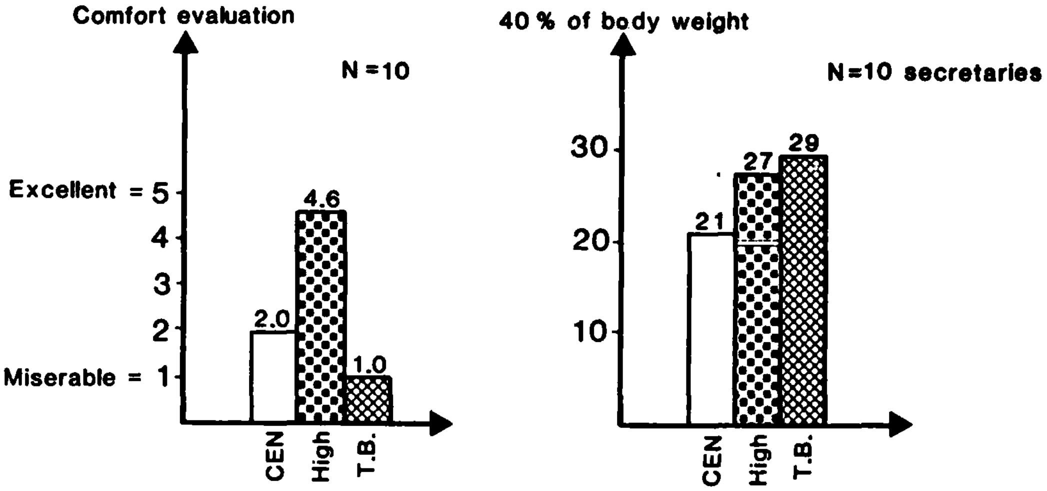

Fig.10 Comfort evaluation P<0.001 Foot pressure P<0.001

C. THE INFLUENCE OF FURNITURE HEIGHT ON BACK-PAIN

Data entry personnnel will have 13 times as many complaints from neck and shoulder pains than traditional office workers (Grandjean 1983).

A group of 13 data-entry personnel with chronic (daily) pains in neck, shoulder and back were investigated. Heights limits 158-175 cm. They were seated on a hydraulic chair with tilting seat. While they were sitting keying-in, the height of the chair and table was altered to a height in which the pain was felt least pronounced. Their daily work station was then adjusted to this height.

Fig.11: Seven out of eleven data-entry operators were able to sit permanently with preserved lordosis in an upright balanced position.

After a 2 month trial period, during which the persons were able to adjust the height easily while working, I found that eleven had adjusted the table height to an average of 72.8 cm. Chair height 54.3 cm. Only two - of the shorter ones - had preferred to remain at the CEN standard height of 65 cm.

In the higher sitting position the average flexion of the back (hip + lumbar joints) was 12.4° less than in the CEN standard position. $P<0.01$. Photoregistration was used for measuring.

Seven out of eleven persons were able to sit permanently with a preserved lumbar lordosis in an upright balanced position without using the lumbar support (fig. 11). The position was very similar to the position taken when sitting on horseback. The remaining four were sitting with lumbar support and with more pronounced flexion of the lumbar region.

Three out of eleven had previous problems with swelling of the legs - they all reported improvement.

Pain indication with visual analogue scale was 35 mm in the higher position compared to 67 mm in the CEN standard position. $P<0.001$. 100 mm indicate severe pain and zero no pain (Huskisson 1974).

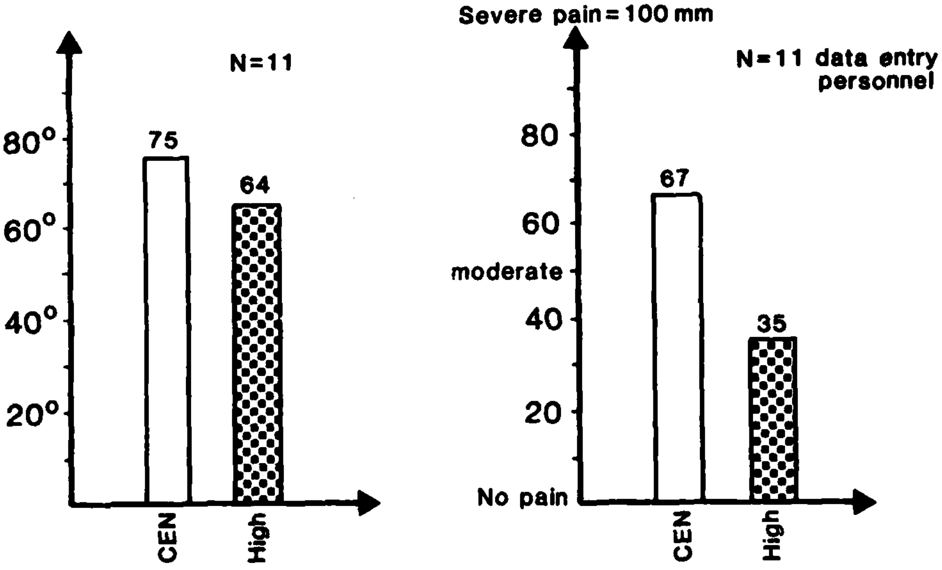

Fig.12. Flexion of lumbar + hipjoint. $P<0.01$ Pain evaluation. $P<0.01$

DISCUSSION

The modern work chair and table may be considered as the most important tool in the industrialized world. Most forms of education, administration and production are more or less physically based on this furniture. Standardization of work furniture have an enormous influence on the well being of us all. It is therefore vital that no forms of standardization should be accepted before the influence on the work posture has been thoroughly investigated.

Unfortunately this responsibility has been completely neglected in such vital areas as the International Standardisation of School Furniture (ISO 1978) and the European Standardisation of Office Furniture by Comittee Européen de Normalisation (CEN 1982). In the anonymous papers presenting the draft standards the only explanation given is that "it is to achieve good posture". Has this ever been experimentally controlled?? Evidently the CEN standard is based on a short term experiment by Joan Ward (1977 unpublished). The CEN standard claims a table height of 72 cm for all non-adjustable office tables. The majority of european office tables are still non-adjustable and the few exceptions can only be adjusted a few cm in height. About 50 years ago the table heights for office clerks were often 100-115 cm and tables for school children about 80-90 cm. In 1978 ISO suggested 70 cm as maximum height of the tables. As the visual distance has remained the same this inevitably leads to more constrained postures.

Lumbar support has been the magic formula accepted by scientists as the means of achieving better work-postures and it is also the ideological background for standardisation. This type of support is of course only effective in the reclined position - with the gravity point behind the sitting bones. Most forms of work, however, take place in the forward bent position with the gravity point in front of the sitting bone. To achieve effective lumbar support a backward sloping seat is necessary. This means that you have to bend even more in the neck region to establish visual contact with the paper on the table. Consequently the back problems of todays office workers are more frequently located in the neck region. On a backward sloping seat the front edge will press into the back of the thigh and tend to rotate the pelvis backwards. To avoid this pressure the chairs have become lower and lower - and this also leads to more constrained postures.

The new CEN standards are evidently only based on the investigation of Joan Ward. In an earlier paper (1969) Joan Ward has demonstrated that school children will only use the lumbar support about 20-30% of the school day. In her recent office investigation she demonstrated that clerks will also only use the lumbar support about 20-30% of the time while reading and writing (this probably represents the time when they take small rest periods).

The lumbar support idea has evidently lead to:

1. Lower furniture.
2. Backward sloping seat.
3. Increased pressure in the knee hollow.
4. Horizontal desk tops.

My investigation indicate that all these factors will increase the back flexion and strain . In this way the lumbar support theory and the standardisation of furniture is under the suspicion of causing the rapid increase of backproblems in the industrialized world. In several meetings, conferences and articles I have again and again asked for an explanation or an excuse for the present type of furniture and standards. Nobody has been able to give me this. Unless the anonymous members of the standardisation bodies are able to give some explanation for the background of their hazardous medical experiments these recommendations should be cancelled immediately. Adjustable chairs and tables should be a natural human right as the people who sit many hours every day know far better what is good for their own backs than any member of the standardisation bodies. In my experiments the people found that the ISO and CEN recommended positions were the most uncomfortable of all the positions tested.

Prevention of back-ache should of course already start at school age. This, however, has been completely neglected by the medical profession. Posture training has been tried to a wide extent but even the most intensive training will result in quite unacceptable working postures (Mandal 1982).

Already at the age of fourteen 60% of Danish school children will complain of head-ache and back-ache (Danske Arkitekters Landsforbund 1981). They believe themselves that it is on account of miserable furniture. When these children start their professional lives the backs have probably already been damaged to a wide extent. When back pain start in office workers the treatment is often disappointing. My investigation indicate that the pain increases with flexion of the lumbar region. It seems logical to reduce this flexion by the methods described. Especially as the pain often will be reduced in the same second as the reduction takes place.

CONCLUSIONS

Standardization of furniture has lead to lower and lower furniture, and this inevitably leads to more constrained sitting postures. This is probably the main reason for the rapidly growing amount of backsufferers. Nobody has controlled the effect of furniture standardization and evidently it has only been to the advantage of the architects, standardization people and manufacturers. To days miserable working postures ought to be registered and studies with automatic camera gives a possibility to compare the postures with various furniture during the daily work.

It is suggested that we in the future to a higher extent consult the consumers and let them decide what type of furniture they prefer.

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DISCUSSION

WILDER, US: What evidence do you have for stating that a greater-than-90° angle between the femur and the trunk is a balanced position? Do you see any problem with some of the anteriorly-tilted seats suddenly moving out from beneath the seated subject, similar to a melon seed squirting out between the fingers?

MANDAL, DA: You asked first about "balanced" or "not balanced" positions. In my paper I showed a drawing by an American orthopedic surgeon, Keegan (J. Bone Joint Surg.: 35A: 589-603, 1953), who has made X-rays of persons lying on their sides. When you lie in bed, you adopt this position; you never lie straight or in a right-angled position. You automatically assume this balanced position when you lie on your side. You also assume this balanced position when you sit on horseback. I suppose all the joints are balanced in this position and that is the way the body as a whole functions best. You mentioned sliding backwards from the seat. I have never heard of any serious problems of this kind. As I indicated, a large part of the population in Denmark is now using forward-sloping seats. You may choose between two types. There is one type which is floating freely, and here there is a remote chance of falling down. If you have a chair with wheels, then, on a hard surface, it is rather lively; but most of the ones that are made now lock in various forward-bent positions, which means that you won't have the risk that it suddenly tilts forward. A more serious problem is that data-entry operators will get back problems after 4 or 5 years of work; the majority of them will then seek medical treatment. We all accept this as happening after a few years of work; however, we are very worried about the fact that a single person may fall on the floor when using a forward-sloping seat.

HAGENA, GE: Could your investigations possibly be brought together with flying personnel or driving personnel? We did some investigations on sitting positions for drivers in our orthopedic clinic in Germany. We thought a backward-reclined position would be better and you showed it would be better in a forward position. Can you comment on that?

MANDAL, DA: Mainly, I have been interested in office workers and school children, but I have also looked at helicopters to get some ideas about the seating problems there. As I mentioned earlier, the drivers of the Vienna wagons sit on a forward-sloping seat: they have done this for hundreds of years and they are in a perfectly balanced position. If they use a flat-surfaced seat (zero slope), then they will have back problems, because when you sit hunched over you are locked in the worst possible position. When you sit in an easy chair -- in tractors and elsewhere they make deep easy chairs -- you cannot work, because you have to bend forward to be in visual contact with the instruments or the ground on a farm; and you have to sit bent in a locked position for around 80-90% of the time. I think it would be an excellent idea to collect data on the old Vienna wagons as they do on horse-back riders. They treat back pains today by horseback riding.

VAN DEN BIGGELAAR, NE: As you may know, modern fighters have inclined seats. The F16 has seat-back angles of 0°, maybe 5°. My experience in the Netherlands is that we have quite a few pilots who have been flying for years and have developed low back pain; and some have even been operated on for herniated intervertebral discs. I was very reluctant to let these pilots fly on the F16 with its backwardangled seat; not because of the tilt angle *per se*, but because of the G-load. Very surprisingly, we have had very few problems with low back pain in the pilots flying in the tilt-back seat, compared to the same pilots flying in the straight-backed seat. This may support your theory that the lumbar spine and hip flexions are much less in the F16 than in previous aircraft, which, in turn, may be easier on the lower spine. Do you agree with that?

MANDAL, DA: I don't know very much about the seating position in fighter planes, but I suppose you have to lie reclined. You cannot sit upright in fighter planes; and, when you have to sit reclined, then I suppose there are additional problems too. I suppose they'll get neck problems.

VAN DEN BIGGELAAR, NE: The problems have switched from low back problems to neck problems.

MANDAL, DA: That's what happened in the office, too. When you use the lumbar support, you are forced to sit leaning backwards; and then you get the problem of neck pressure, because you have to bend the neck much more than before.

VAN DEN BIGGELAAR, NE: Then there is the dynamic load on the cervical spine because of the turning of the head under the G-load. That is another problem though. My experience in the Dutch fighter community is that lower back pain with the tilt-back seats is much less frequent than in older types of aircraft.

VAN INGEN, US: How are you measuring the height of your table? I was looking at your picture and I can't figure out if it is the height to the base of the table or to the slope.

MANDAL, DA: It is determined to the nearest part of the table. In fact, the book is placed about 8 or 10 cm higher, which means that the 92 cm is a minimum. The book is lying in a position about 100 cm high, and that is quite high, because the girl is 171 cm tall.

VAN INGEN, US: So it is to the base of the table.

MANDAL, DA: It is to the lowest part of the table; and the height of the chair is measured at the center of the rotation, because that's the only part that remains permanent.

VEHICLE VIBRATION AND BACK PAIN

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SUMMARY

Although it is often suggested that chronic low back pain in professional drivers is related to vibration or posture, we have only a limited theoretical framework to work with. Well organised, prospective epidemiological studies may demonstrate that chronic low back pain in drivers or pilots is related to "high levels" of vibration or "poor" posture. However, they will get us little further without the theoretical base.

In this paper, it is assumed that chronic back pain is dependent primarily on disc degeneration and that disc degeneration, in turn, arises from fatigue-induced damage to the vertebral end-plates or to the tissues of the annulus. It will be shown that in either case, time to failure is related to an exponential function of stress such that instantaneous stress maxima are more important than long term (e.g. r.m.s.) stress values. We usually assume that some frequency weighting function is needed to predict, from vehicle vibration, the spinal stress that may lead to malfunction. This function may be based on equal discomfort contours, biomechanics data or a simple model.

It is shown that basic assumptions on the effects of stress and on frequency weighting can markedly affect the evaluation of particular vibration environments.

INTRODUCTION

There have been a number of epidemiological studies of the health of vehicle drivers and these are reviewed in Andreyeva-Galanina and Karpov (1) Dupuis & Zerlett (2), Hasan (3), Heide (4), Heide & Seidel (5), Kohl (6), Sandover (7), Vihko & Hasan (8) and Wickstrom (9). Although spinal disorders, digestive and cardio-vascular problems have been observed, one finds, in general, that spinal disorders are the most investigated and offer reasonably consistent findings. The evidence is not fully convincing, as few of the studies meet the requirements of Troup (10) vis standardised data gathering and matching controls coupled with prospective investigation. However, the data generally suggest an increased and/or premature risk to health typified by the data of Kohne et al (11) illustrated in Fig 1.

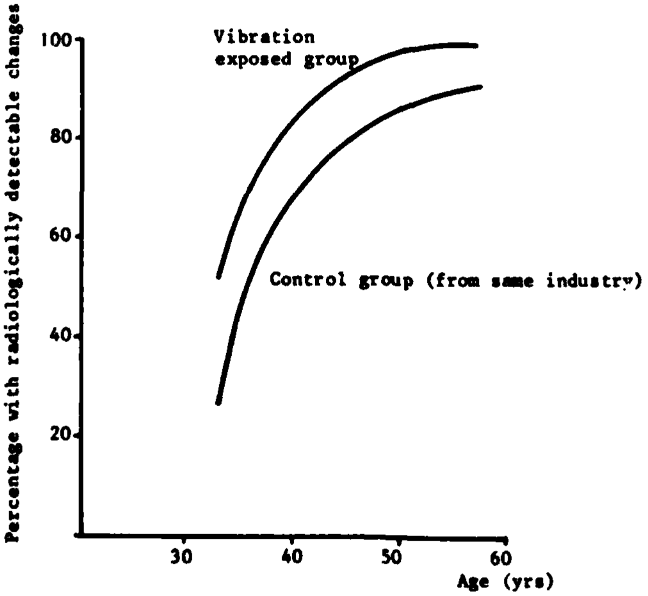

Fig. 1. Morbidity of drivers exposed to vibration (after Kohne et al (11))

These data relate to working with vehicles where vibration is a significant element of the environment. However, they do not necessarily mean that vibration is the only aetiological factor - both Troup (10) and Shanahan (12) have emphasized the role of posture - nor do they throw much light on the relationship between vibration and degree of risk. With the current state of knowledge, even the best epidemiological investigations can only demonstrate that chronic low back pain in drivers or pilots is related to "high levels" of vibration or "poor" posture. To obtain objective data sufficient to generate dose-response relationships, one needs precise clinical criteria, occupational case-histories and environmental descriptions and these demand some theoretical framework. In the case of vibration and back pain we need to know the following:

(i) the source of back pain in terms of identification and location of malfunction

(ii) (assuming that it has an influence) how vibration leads to malfunction together with the effect of other influences on malfunction

(iii) the relevant dynamic parameters (acceleration, displacement or force?) and the degree of effect

(iv) the influence of time scale and frequency

(v) the relationship between some measurable quantity (e.g. seat acceleration) and the relevant dynamic parameter at the point of malfunction.

The aim of this paper is to throw some light on the five points above. Then, the consequent requirements for environmental descriptions (for use in epidemiological work) will be considered, using available data and some reasonable assumptions.

THE SOURCE OF BACK PAIN

Pain is an "abnormal emotional state" (Wyke (13)) and low back pain is notoriously difficult to deal with. It has psychological as well as physiological and physical aspects. If one limits the discussion to chronic low back pain, then one has to consider both mechanical interference and inflammatory action. However, one can argue (Nachemson (14) & (15) and Sandover (7)) that the intervertebal disc and its degeneration are central to considerations of chronic low back pain. The lower lumbar vertibrae appear to be the most involved.

MALFUNCTION AND MECHANICAL LOADING

The intervertebral disc relies on nutrient diffusion through the end-plates and annulus and the nutritional condition at the centre is probably precarious. Both end-plate malfunction and annulus malfunction can therefore be expected to lead to disc degeneration and I have hypothesised (Sandover (16)) that dynamic compressive forces at the end-plate or dynamic loads on the annulus (arising from shear, bending or rotation of the intervertebral joint) can lead to fatigue-induced malfunction.

Poor or constrained posture can be expected to lead to muscle fatigue and to muscular, articular or ligamentous pain. In addition, posture affects the frequency-dependent vibration transmission behaviour of the body (Sandover (17)) and there is some evidence to suggest that dynamic intradiscal pressures are related to posture (Sandover & Andersson - paper in preparation). Posture is not considered further in this paper, but it is clear that it has to be taken into account in any occupational case-history.

DYNAMIC PARAMETERS, DEGREE OF EFFECT AND TIME SCALE

The hypotheses mentioned above refer to fatigue-induced failure, compressive forces at the endplate and shear, bending or rotation of the intervertebral joint. Compressive forces at the end-plate clearly arise from compression of the intervertebral joint, but (in the form of intra-discal pressure) they may also arise from bending or torsion at the intervertebral joint (Berkson (18) Schultz et al. (19)).

The influence of fatigue-induced failure is important as regards degree of effect and time scale. The fatigue process in metals is complex (Smith (20)). However, under cyclic loading there is usually a relatively simple logarithmic relationship between the applied stress and the number of cycles to failure. *Lafferty* and Raju (21),(22) have developed a function to predict the affect of dynamic loading (in bending) of bone (including human vertebral bone), taking into account the static failure characteristics of the bone and the cyclic frequency. The number of cycles to failure (N) is given by:

$$N = \left(\frac{\sigma_u}{\sigma}\right)^x$$

where σ is the applied dynamic stress, σ_u is the static failure stress and $x = 7.7$.

This is illustrated in *fig. 2*.

Also illustrated in fig. 2 is an indication of the relationship found by Carter et al. (23) for bony tissue under compression.

These data could be expected to apply roughly to the intervertebral endplates and subchondral bone but not necessarily to annular tissues. However, Weightman (24, 25) has investigated the fatigue properties *of* femoral articular cartilage and his relationship (with an assumption of application to a single cycle to failure) is also illustrated in fig. 2.

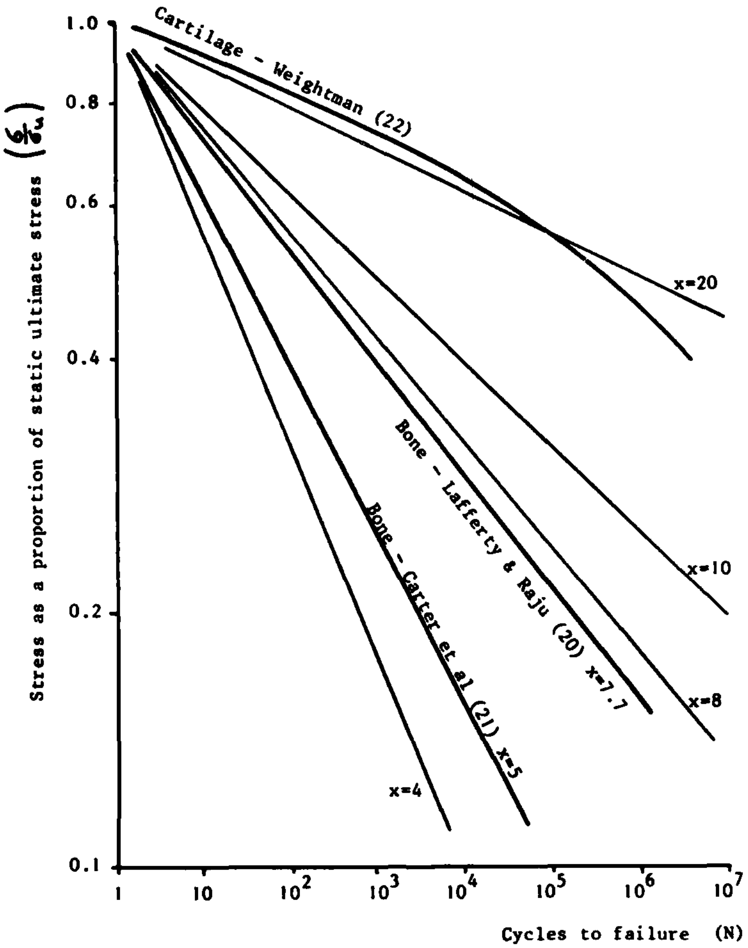

Fig. 2 Fatigue life of animate tissues.
Straight lines represent the functions $N = \left(\frac{\sigma}{\sigma_u}\right)^{-x}$

If one assumes that mechanical loading and fatigue are at the root of mechanically induced malfunction of the disc then, whatever the actual hypothesis, fig. 2 shows that the Lafferty & Raju relationship will be a useful description with x somewhere between 5 and 20.

This has an important consequence. An exponential function is involved so that an increase in dynamic stress or a reduction in strength has a disproportional effect compared with increase in duration of exposure. This would suggest that current methods of vibration evaluation, based on weighted r.m.s. acceleration, underestimate the risk to health if the vibration contains significant peaks. One feels intuitively that this is probably true and Griffin & Whitham (26) have successfully applied the r.m.q. (4th power equivalent to r.m.s.) method to predicting subjective intensity. The line for x=4 is illustrated in fig. 2.

One can carry the engineer's approach to metal fatigue one step further and apply the Palmgren-Miner hypothesis to obtain a dose-response relationship. The hypothesis states that the degree of fatigue damage is given by $\sum_\sigma \frac{n_\sigma}{N_\sigma}$
where n_σ is the number of cycles at a particular stress level σ
and N_σ is the number of cycles for failure at that stress level.

The effect of a particular vibration environment is then given by $\sum_\sigma \frac{n_\sigma}{(\sigma_u/\sigma)^x}$ or (expressed as a 'dose') by $K \sum_\sigma n_\sigma (\sigma)^x$ where K is a constant related to the strength of the tissue.

A similar function with x=4 is currently proposed for revisions of ISO 2631 and BSI DD32.

Using this approach one can establish a dose-response relationship sufficient to compare and enumerate different vibration environments met in epidemiological investigations. This is possible without detailed knowledge of the damaging process provided that one has a value for x and provided that one knows the relevant dynamic stress parameter (e.g. compression or bending) and can estimate its magnitude.

EXTERNAL MEASUREMENTS TO ESTIMATE INTERNAL STRESSES

Although it would be preferable to measure stress or even strain at the end plate or annulus, this is clearly impractical. We need to estimate these from external measurements (on the person, the seat or the vehicle). It is usual to measure the seat acceleration and then to apply a frequency weighting function. This does not allow an estimate of an absolute value of internal stress or strain, but the method is sufficient to facilitate comparison of different seat vibrations in terms of their predicted effect.

Very often (e.g. ISO 2631) the weighting function is developed from a pragmatic standpoint, taking into account available laboratory data and information on the effects of particular types of vehicle.

An alternative is to use man as his own measuring device and use contours of equal subjective intensity. This is a valuable approach in a complex situation. Unfortunately, there are very few data on subjective response targetted on sensations in the lumbar spine. One also has to consider if transient (i.e. obtained at an experiment) pain or discomfort are good measures of the stress or strain under consideration.

Another alternative is the use of a biodynamic model or biodynamic data. The simple compressive model used in the 'Dynamic Response Index' (27, 28) is a good example of the former. Seat to head transmissibility data are sometimes suggested as a frequency weighting function. However, head-nodding is an artifact that may affect most of the available data and the input force:acceleration transfer function (corrected for unsprung mass) may give a better estimate of compressive forces in the lumbar spine. The ISO 2631 weighting function, the DRI model response and a typical apparent mass spectrum are illustrated in fig. 3.

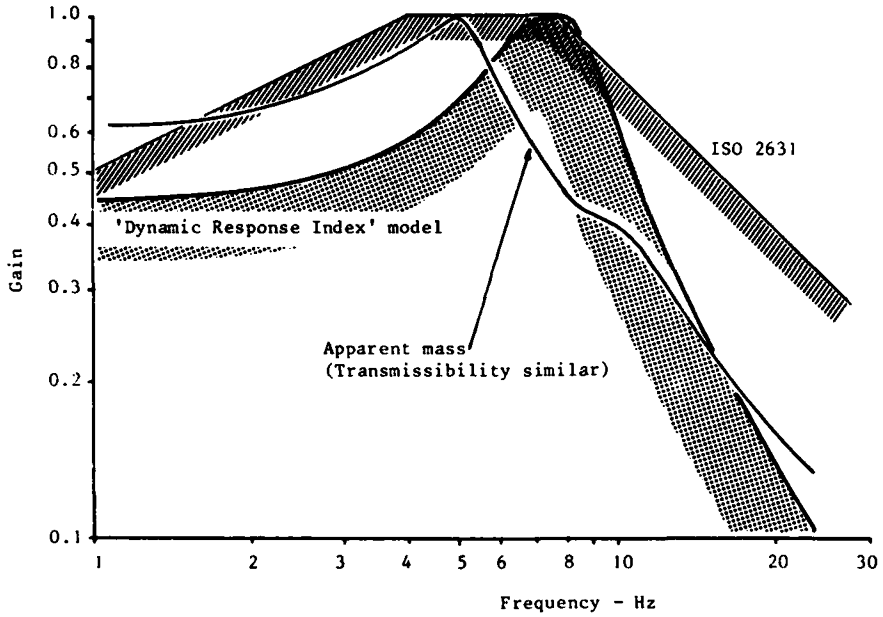

Fig. 3 Possible weighting functions

However, a simple compressive model alone may be insufficient to explain vibration stress in the lumbar spine. I have suggested (17) that bending (arising from a rocking motion of the pelvis) may be the source of resonance effects rather than buttock or spinal compression (see also Frolov & Potemkin (29) and Huijens (30)). In a reanalysis of the data of Christ and Dupuis (31) we have shown (Sandover & Dupuis - paper in preparation) that there can be about a degree of relative angular motion at the intervertebral joint during exposure to sinusoidal seat vibration of 1m/s^2 r.m.s. The spectrum of response shows a very sharp roll off (≈ 24 dB/octave) above about 4 Hz, and a weighting function based on these data would be even less influenced by high frequency vibration than the D.R.I. or apparent mass models.

This raises the question of different bases for the most simple model. The D.R.I. model is based on the compression of the spring of a single degree of freedom system. This has a 12dB/octave roll off at high frequencies. A model based on acceleration of the mass (transmissibility) or force would have a 6dB/octave roll off. Both indicate a rather sharp resonance and do not satisfy the pragmatic standpoint mentioned above. However, one must be aware that the averaging process tends to smooth data and remove sharp resonances so that group data (whether from biodynamic or subjective responses) often hide individual behaviour that changes rapidly with frequency.

PRACTICAL APPLICATION OF THE ABOVE

a) Relevance of fatigue-induced failure hypotheses

It may sound far-fetched to suggest that vehicle vibration leads to material fatigue in human tissues. However, it is shown below that it may be possible. Indeed Carter et al (23) suggest that fatigue resistance is so low that remodelling must occur so that bone fatigue damage accumulation is physiologic rather than pathologic.

To obtain an idea of the relevance of material fatigue we need to know the failure stress for the spinal tissues and the applied repetitive stress arising from exposure to vehicle vibration. I have calculated (7) that a vehicle vibration of about 2 /s^2 r.m.s. will lead to 0.8M.Pa (peak to peak) disc pressure. Our analysis of actual disc pressure measurements (Sandover & Andersson - paper in preparation) suggests that the value may be about 1M.Pa. These values are about one tenth of the pressure for end-plate fracture. We can obtain a similar ratio using a gross approach: 2 m/s^2 r.m.s. at the seat will be (after taking resonance into account) equivalent to some 10 m/s^2 peak to peak at the lumbar spine. The Dynamic Response Index indicates a 50% probability of injury at 22g - i.e. approx. 220 m/s^2. However, this refers to gross vertebral damage and halving this value for minor damage is not unreasonable. Then, once again, the stress from 2 m/s^2 vibration is roughly one tenth of the failure load. If we consider bending and annular stress, I have calculated (7) the failure value to be at about 20° bending. Our analysis of spinal motion referred to above indicates that about 2° of bending between adjacent vertebrae may be expected at 2 m/s^2 r.m.s. Thus is each case, it seems that the stress arising from 2 m/s^2 r.m.s. is about one tenth of the failure stress.

If we consider vibration at 5 Hz (probably the most damaging frequency), then a working day's exposure results in about 1 x 10^5 reversals. If we now return to the Lafferty and Raju function for $\sigma/\sigma_u = 0.1$ and $x = 8$, failure is predicted to occur at 10^8 reversals (i.e. 1000 working days). If $x = 5$ (as from Carter et al) then failure is predicted to occur at 10^5 reversals (i.e. 1 day).

Clearly fatigue failure is a possibility, though much depends on the value of x that applies and on the recovery processes involved.

b) Expected influence on evaluation methods

To consider the influence of the various possible approaches to vibration evaluation, a variety of exponential functions and frequency weighting functions were applied to a vibration signal. The following were used:

> Scoring methods: r.m.s.; r.m.q; a simple range counting method (as used for fatigue work - see Dowling (32)) coupled with Palmgren Miner summation and using an exponential value of $x = 8$
>
> Frequency Weightings: unweighted; ISO 2631 weighting; DRI model.

This was carried out using analogue weighting networks applied to the signal before digital treatment on a CED 502 data analysis system. Prior to digitisation, all signals were low-pass filtered (100 Hz cut off, 24 dB/Octave)

Random signals, essentially flat but rolling off at 18 dB/octave from a set frequency, were used to simulate vehicle vibration. To differentiate between 'low',' medium' and 'high' frequency acceleration spectra, the roll-off frequences were set to 5, 15 and 50Hz. The unweighted signals all had a crest factor of the order of 2.5.

The scores arising from the various methods of evaluation were normalised so that the unweighted score for each type of signal and each evaluation method equals 100. The resulting scores are given in Table 1.

Weighting	r.m.s.	r.m.q.	range count	signal
Unweighted ISO weighting DRI model	100 85 56	100 86 56	100 33 0.9	Roll off @ 5Hz
Unweighted ISO weighting DRI model	100 80 57	100 83 58	100 39 1.6	Roll off @15Hz
Unweighted ISO weighting DRI model	100 43 28	100 45 28	100 0.1 0.002	Roll off @ 50Hz

TABLE 1

Comparison of the scores of different weighting methods and different methods of evaluation for three types of signal. Scores are normalized to the unweighted score.

As one might expect the weighting method influenced the resulting score. Also, the 'high' frequency signal affected the pattern of this influence.

The figures for r.m.s. and r.m.q. are similar. This suggests that although r.m.s. and r.m.q. give difference scores, this difference is consistent and one can predict one from the other. Griffin & Whitham (26) refer to ISO weighted r.m.s. and r.m.q. scores from a variety of vehicles and their data show the r.m.q. score to be consistently about 30% higher than the r.m.s. score. This all suggests that the r.m.q. is of no real value - it doesn't differentiate between vehicles better than r.m.s. and it can be predicted from r.m.s. anyhow. However, the analysis here (and probably the vehicles measured in (26)) involves relatively low crest-factors. The r.m.q. probably proves its value at higher crest factors.

The range-count score is influenced much more by the various weighting methods. This, however, is not primarily because $x = 8$ is large: If one takes the eighth root of the range-count score to mirror the fourth and square root of r.m.q. and r.m.s., then the resulting pattern of effects is closely similar to that for r.m.s. and r.m.q. This raises the question, should we indeed take roots when attempting to obtain a dose-value. The root simply brings the score to an 'equivalent acceleration'. It does not give a 'dose' and it tends to camouflage the difference between signals as regards their relative effect.

Unfortunately, it was not possible to investigate high crest factor signals, nor the effect of the phase characteristics of the weighting function. Clearly, both need to be done. The phase characteristics of a weighting network can be expected to affect peak values and higher crest factor signals can be expected to have a greater influence on scoring methods using large exponentials (i.e. where $x \geqslant 4$).

The range-count method is rather crude and may underestimate fatigue (Dowling 32). It would seem therefore that the differences found in this very simple experiment probably underestimate the differences in score arising from different weightings and evaluation procedures.

CONCLUSIONS

The epidemiological evidence suggests that occupational exposure to vibration may lead to earlier onset or increased incidence of degeneration in the lumbar spine. However, we wish to develop dose-response relationships for general application, we need to know much more. Different scoring methods and weighting functions can lead to markedly different evaluations. Epidemiological investigations should include measurement of vibration, but should not rely only on simple evaluation methods such as weighted r.m.s. acceleration.

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DISCUSSION

QUANDIEU, FR: You have advanced the hypothesis that the first element that leads to chronic pain in the spinal column is the fatigue of biological tissues. Another question that could be asked is: "Why not the reverse"? Why could it not be the pain which leads to fatigue? This is the first comment. The second, and probably the most important one, is that the concept of fatigue is completely ignored in biology. Absolutely no definition concerning the fatigue of biological tissues exists; none at all. Yet, you attribute the fatigue of the biological tissues to fatigue of the mechanical-type of structure. So, for a series of loadings and unloadings, there exists a degradation of the mechanical properties of the structures which leads to the Lafferty (Aviat. Space Environ. Med. 49: 170-174, 1978) and Carter (J. Biomech. 14: 461-470, 1981) models, which you have taken as correct. On the contrary, I believe that they are both wrong, for at least two reasons. First, in a biological medium, there is no excitation which can result in rupture of the system in an environment with admissible levels of vibration; thus, it is not necessary to look for ruptures. Second, it is possible that another independent phenomenon , called porosity, exists. This could help to explain why there is a stabilization of the structure in spite of the presence of vibration.

SANDOVER, UK: This is a problem because, in general, we assume that biological materials repair themselves anyhow. However, I'll give you one example of a possibility, which we have heard mentioned three or four times today: microfractures in the spine. One possibility is that one does get microfractures in the vertebral body, just under the cartilaginous endplate. These microfractures occur with ordinary levels of vibration; and, normally, it doesn't really matter. However, when they repair, they repair with the wrong tissue, so then there is a poor situation for nutrient flow between the disc and the body of the vertebrae. That's one hypothesis that I've worked on. I agree that gross fracture perhaps isn't the mechanism, because this would imply that the whole vertebral body is breaking down. Rather, my hypothesis is that small fractures lead to other problems.

QUANDIEU, FR: I am not convinced that this is an excellent remark because the work of Van Sickle (AGARD Conference Proceedings No. 322, pp. 1-1 to 1-3) and Eurell (Report AFOSR-TR-82-1087) demonstrated that the same type of microfractures occur in alveolar tissues following shocks. Therefore, there are two profoundly-different excitations that can lead to the same biological phenomenon, and this is at least one too many.

IN-VIVO EXPERIMENTS ON THE RESPONSE OF THE HUMAN SPINE TO SINUSOIDAL G_z- VIBRATION

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Abstract

The transmissibility of the human spine to vertical G_z-vibration was up to now investigated mainly by measurements on the body-surface and the head. As it is known that vibration transmission between skin-soft tissue-bone is not linear, we thought it necessary to insert percutaneous K-wires into the spinous process for direct measurements. In 11 healthy subjects at various defined heights of the spine including the head the amplitude ratio was measured to the sacrum and in comparison to the shake table. The tests were performed in standing and sitting position on a shake table with vibration control system. The natural frequency of the spine was confirmed by additional in-vitro tests on isolated lumbar spine segments under special conditions.
Results:
The human spine acts as a vibration system with three defined areas of resonance. The spinal column causes an absorption up to the head. Rigid body segments as well as fusion of spinal segments lead to increased strain in neighbouring segments. This was proved by in vivo as well as in vitro investigation. A new set-up for in vitro tests was developed.

Introduction

In order to resolve an aspect of the biomechanics of the human spinal column a study was performed in which the vibration and absorption of the spinal column in response to acceleration was measured from the spines of healthy subjects and lumbar material gained from autopsies.
Todays technological environment exposes a large variety of people to mechanical vibrations and partly to extreme accelerations. Numerous studies exist concerning the effect that total body exposure to vibration has upon the circulatory system, the respiratory function and the sensory organs. There are also studies which deal with the subjective feelings and also the effects of vibrations on the sceletal system.

In connection with the national and international standardization to avoid harmful effects caused by such mechanical vibrations the derived relevations were acknowledged by the German Industrial Norm Organisation (DIN, 1974) and by the International Organisation of Standardization (ISO, 1984).
From the past known publications which dealt with the influence of vertical forces upon the spinal column each study was concerned with a specific segment of the spinal column, for example the cervical spine and the lumbar spine. Various measuring techniques were applied from which conclusions were drawn concerning the total spine (tab. 1).

table 1: Response of the Human Spine to Vertical Vibration

Author	Year	Examination	Method
DIECKMANN	1960	head/shoulder	accelerometer
DUPUIS	1960	cervical spine	cinematography
CHRIST and DUPUIS	1963	cervical spine	x-ray- cinematography
KRAUSE	1963	lumbar spine	strain-gauge
KRAUSE	1963	L_1 - Th_4	galvanometer with reflectors
LANGE and COERMANN	1965	$L_{3/4}$ - $L_{4/5}$	Hg - tubes
CHRIST and DUPUIS	1966	lumbar spine	K-wire-method
GRIFFIN	1982	head	accelerometer
GARG	1982	head	accelerometer

CHRIST and DUPUIS (1963 and 1966) are presently the only authors who with the use of x-ray cinematography of the cervical spine and with a Kirschner-wire method of the lumbar spine were able to make direct measurements conducted from the vertebrae. Their results described the resonance at a frequency of 4 Hz. This conclusion corresponds with the studies made by MÜLLER (1939), SCHMITZ (1959) and COERMANN (1963) who performed measurements from the head. They made these conclusions and described them for the entire body. These data are presently still recognized as the international norm. These findings are quite different from those found by acceleration measurement of GARG (1982) who described 5 peaks between 2 and 43 Hz (fig. 1).

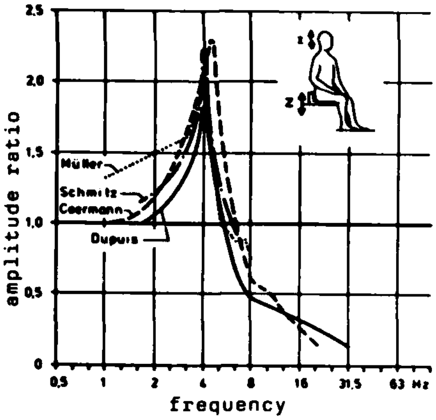


fig 1: Transmission of sinusoidal vibration from seat to head in vertical direction-Z
DUPUIS, 1984

As can be demonstrated with the x-ray of a 44 year old patient who underwent a spinal fusion between L 5 and S 1 an often subsequent result is spondylarthrosis in the neighbouring intervertebral joints. These types of changes are also often found in connection with congenital ankylosis of two vertebrae or following ankylosing spondylitis (fig. 2).

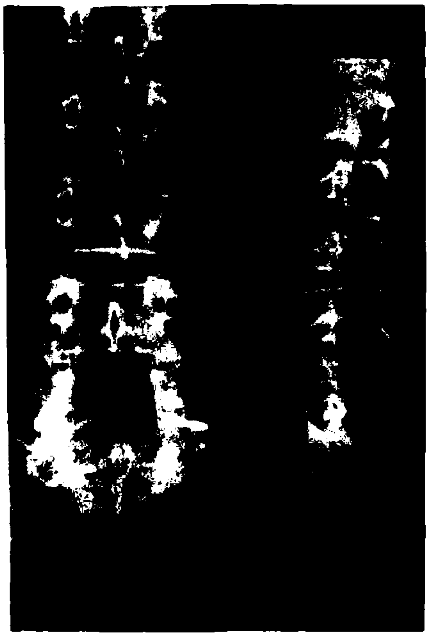


fig 2: x-ray: male patient, 44 yrs. spondylarthrosis of the lumbar spine after spondylodesis L_5/S_1

Hypothesis I

Based upon our knowledge derived from literature it is known that the human spinal column behaves like a vibration system (e.a. v. GIERKE, 1976). From this fact we derived the question whether the system is influenced by such changes as for example spinal fusion, ankylosis of vertebrae and if such disturbances can lead to pathological changes at normal neighbouring spinal column segments.

In order to prove this hypothesis it appears necessary to clairify the question as to how this vibration system of the spinal column actually behaves. It was therefore first of all necessary to measure the acceleration of patients with a normal spinal column.

Method

After ARTMANN et al.(1976) realized that the transmission from bone - subcutaneous tissue - to skin was not linear examinations were then performed with accelerometers by percutaneously inserted Kirschner-wires fixating them at the spinous process of the vertebral body. Transmission from the vertebral body - spinous process - Kirschner-wire to the accelerometer was examined in pre-tests. This was performed on 16 spinal segments each consisting of 1 to 3 vertebrae on a shake table with an acceleration were performed with an accelerometer from the Fa. BRÜEL and KJAER Type 4315, Delta shear. The vibration was derived from a control and analytical system from the Fa. GenRad, 2503 (fig. 3).

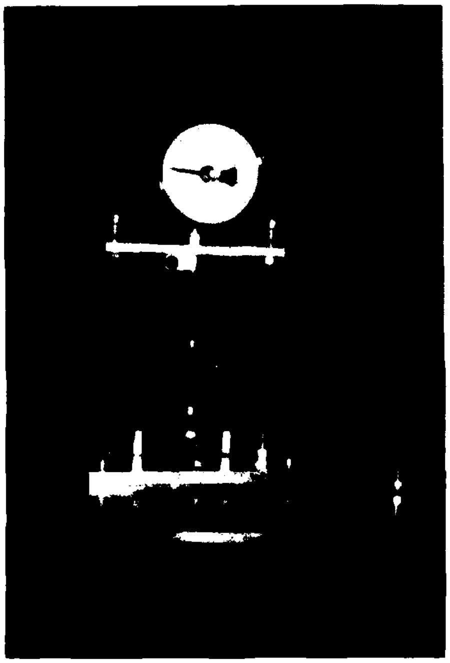
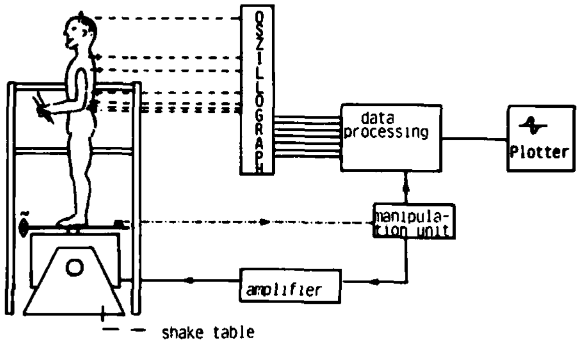


fig.3: Pilot model for acceleration measurements (cervical segment on the shaker)

The isolated insertion of Kirschner-wire with a diameter of 1.8 mm and a distance between the bone and the accelerometer of between 2 and 3 cm was checked, the preparations were treated as follows:
The transmitting lenght between the vertebral body and the spinous process was varied with an insertion depth between 1-2 cm. Exposing the spinal segments to a constant pressure,the set-up of the test was similar to that used by KAZARIAN (1972). It was possible to prove a direct linear transmission of the acceleration with a use of those pre-tests. In other words, the acceleration measured corresponded to the stimulation.

Procedure

We now carried out measuring the acceleration on healthy subjects. The acceleration measurements were performed on 11 volunteers of which 9 were males and 2 were females with an average of 26 years, 1.75 m tall and weighing 69 kg. The subjects were positioned on the shake table and exposed to sinusoidal vibration of constant acceleration of 0.2 g and between 3-40 Hz in the Z-axis. The vibration was introduced in the standing and sitting position a) at the feet b) at the pelvis (fig. 4).



vibration unit: GenRad 2503 vibration control system
shaker : R M S 1507

fig.4: Experimental set-up: Human subject - shake table

The possibility of any pre-existing pathological spinal column affections were ruled out with first performing x-rays. After the testing we also checked the vertebral body which was being used for measuring purposes with an x-ray and marked it with rings.
The set-up of the experiment was devised so that the position and posture could be maintained relatively unrestricted troughout the examinations. The Kirschner-wires were inserted with a long lasting local anesthetic. The following levels of the spinal column were considered representative: L 5, L 4, L 1, Th 6, C 7. For an isolated examination of the spine excluding the influence of the lower extremities an additional accelerometer was fixed at the sacral bone and connected to the register. Another accelerometer was shepped on the head (fig. 5/6).

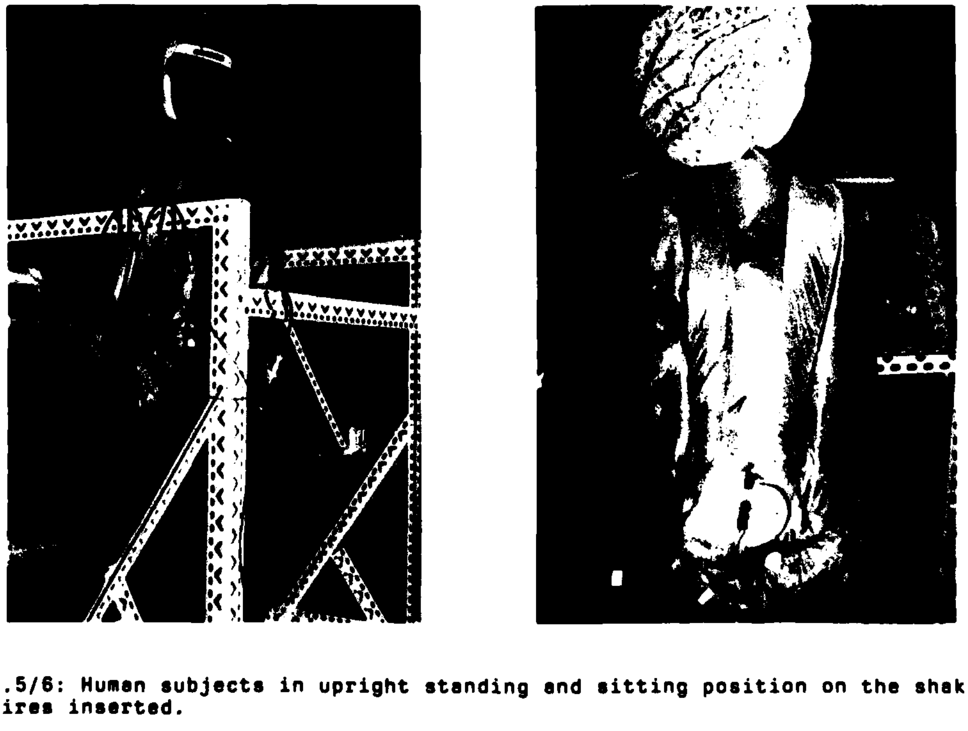


fig.5/6: Human subjects in upright standing and sitting position on the shaker K-wires inserted.

The measured accelerations at the individual vertebrae were converted by the system into the amplitude ratio and these values were then incorporated into a curve in relation to the frequencies. The amplitude ratio is the result of the quotient of the amplitude derived at the measuring point and from the stimulating amplitude. For the evaluation of the isolated spinal column response the stimulated amplitude at the shaker and the amplitude measured at the sacral bone were taken into account.
For our purposes the resonance frequencies require special attention because this is where the response is liable to be pathologic. It is necessary to avoid any large increase of strain within resonance areas.

Results

For illustration one subject demonstrates in the upright position first the situation including the lower extremities with the point of reference at the shake table. Secondly the point of reference is the sacral bone which relates the isolated individual curves resulting along the spinal column up to the head (fig. 7/8).

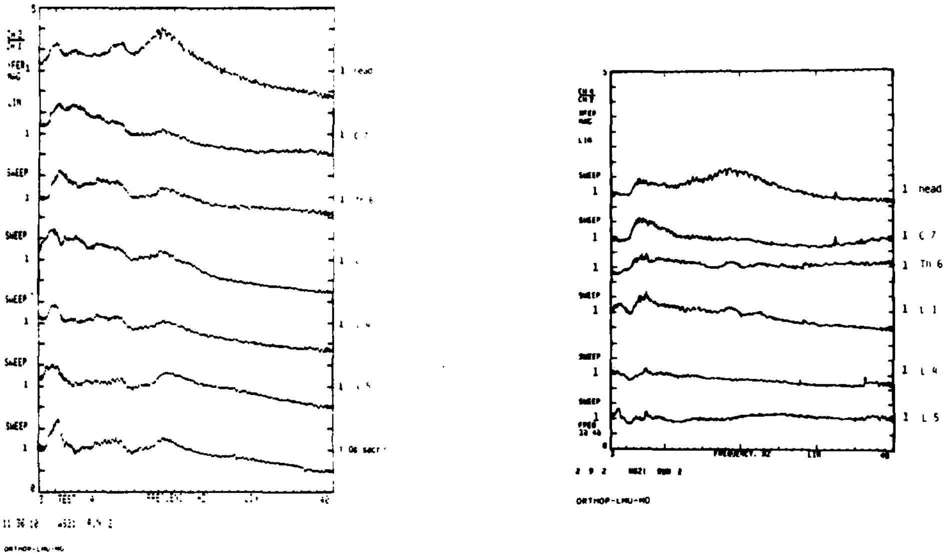


fig.7/8: Response to the vertebral column of one subject with reference to the shaker and to the os sacrum.

In regard to the first situation:
Combining the legs with the pelvis shows a definite increase of all the resulting potentials reaching a factor of 1.7 at 4 Hz. There is a small wave-like increase reaching a factor 1.1 at 8 Hz and an additional increase at 20 Hz at the head atteining a value of 1.8.
In the second case:
The only increases which can be demonstrated are at L 5 and L 1 reaching the factor 1.3 at 4 Hz. In practically each segment there is a demonstrative increase of the factor up to 1.4 at 8-9 Hz. In this situation the resonance at 20 Hz yields a factor 1.5 which is less.

In both cases it is possible to detect 3 resonance areas. The apparent fact is that the increase at 4 Hz for the entire body at the spinal column is very insignificant, especially at L 5 and L 1. The isolated measurements from the spinal column show an obvious increase at 8 Hz.

For each of the individual measuring points in the spinal column a mean value was determined from the single curves derived from the 11 subjects. They are determined in the standing and sitting position. These curves only represent the response of the spinal column which was measured by the amplitude of the sacral bone to the corresponding spinal column segment.

While standing, measured at a frequency of 4 Hz, L 5, L 1 and C 7 showed a marked increase of acceleration, as a result of augmented strain. The increase at 8 Hz is qualitatively equally large, the difference is not significant. This demonstrates that the thoracic spine is set into motion together with L 1 an d C 7. At L 4 and especially at the head there is only a minimal increase. The vibrations at these levels are well absorbed (fig. 9).

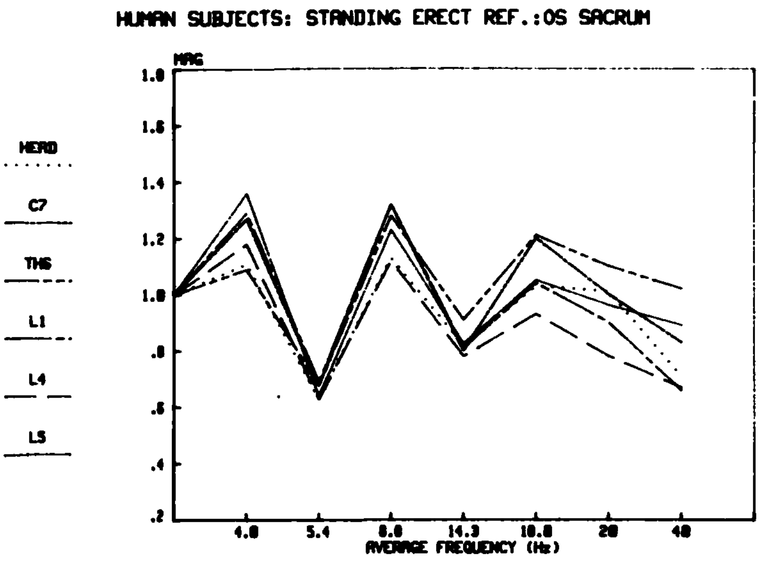


fig.9: Average frequency response
Human subjcts: standing position
Reference point: os sacrum

The sitting position demonstrated that the increase at 4 Hz significantly decreases, since the body weight is less. Conversely the response of the spinal column vibration at 8 Hz remains unchanged. It is not possible to interpret reliably the values beyond the frequency range at 20 Hz. There is also an absorption for the head (fig. 10).

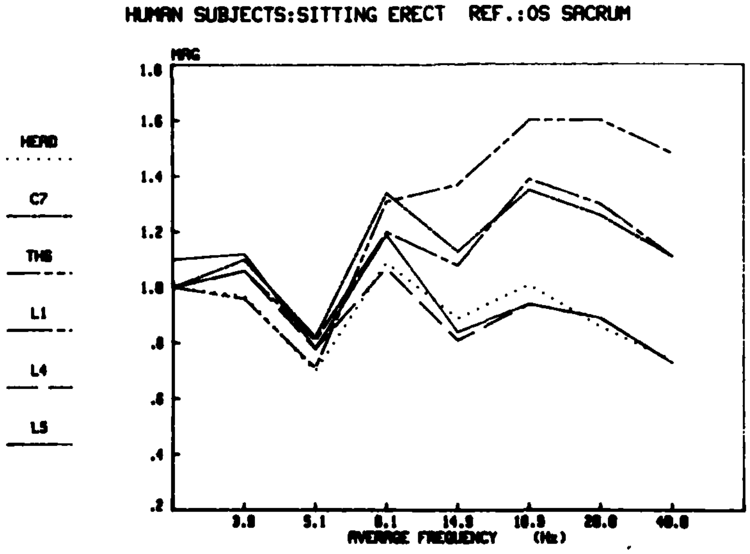


fig.10: Average frequency response
Human subjects: sitting upright
Reference point: os sacrum

The first question can therefore be answered as follows:
It is possible to demonstrate 3 resonance areas at the spinal column from which the range at 7-10 Hz can be designated as the independent resonance of the spine.

At the head the vertically introduced vibrations are absorbed up to 40 % at every frequency. The absorption varies at the different levels of the spinal column at the given frequencies.

Hypothesis II

Further investigation is required as to whether and how pathologically altered spinal columns can influence these results. This can be experimentally tested either in vivo on sui-

table patients or in vitro on spinal columns from autopsies. The reliability of the examination of patients seemed only to be of value in a prospective study.
First it was necessary to clairify whether the complicated biomechanics of the spine could be reproduced in correlation to the response of the above experiment. The lumbar spine appeared suitable to us, also especially because of it's clinical relevance.

Procedure

During the pre-testing we used a constant potential at which however no resonance could be determined.
The reconsideration that the masses overlying each spinal segment are more or less unrestricted in their mobility, led us to the idea to construct an experiment with frictionless placed masses. The set-up of the experiment was devised so that the exerted force could simulaneously be measured cranially and caudally (fig. 11)

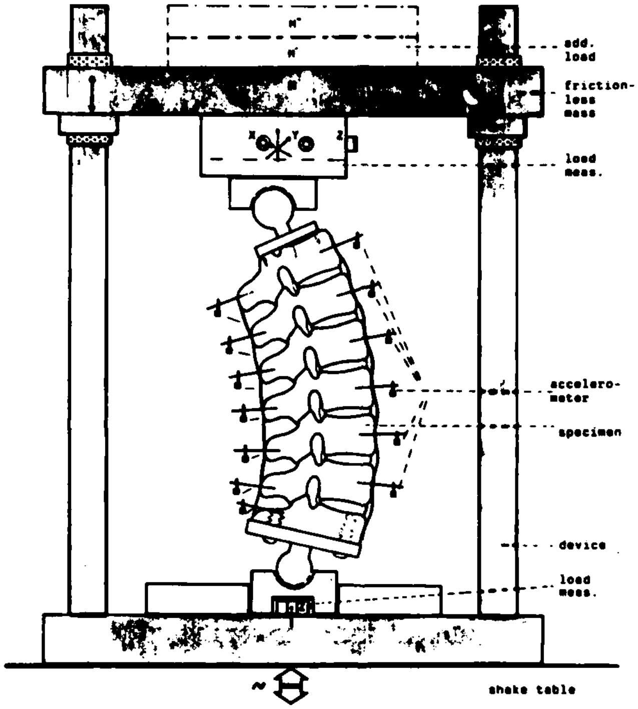


fig.11: Experimental device for the lumbar spine vibration

The appropriate masses, correlating to the body weight according to how NACHEMSON (1969) had calculated the exerted force on segment L 3, revealed an increase above factor 4.
By using a 35 kg load we created a similar transmitting situation for the lumbar spine which was an adaquate adaption of the in vivo situation. The results are presented here logarithmically. The lumbar spine by itself without any other body involvement reveals now to only have a resonance range between 6-10 Hz (fig. 12).

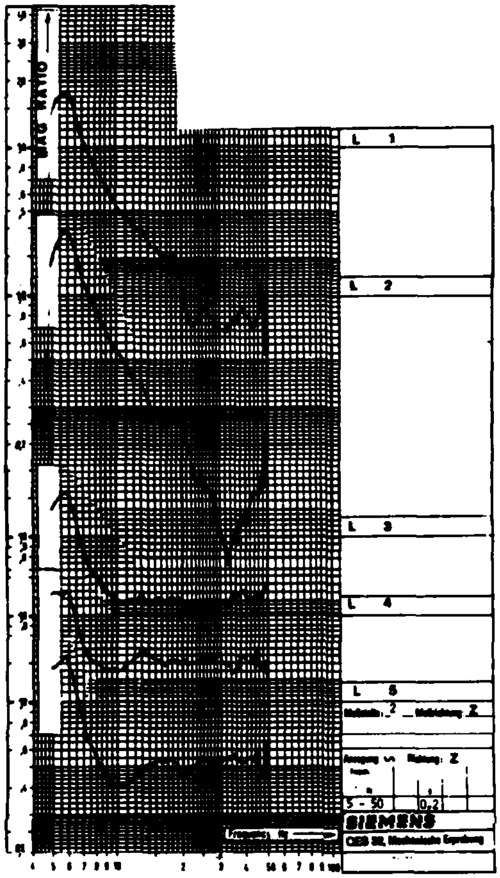
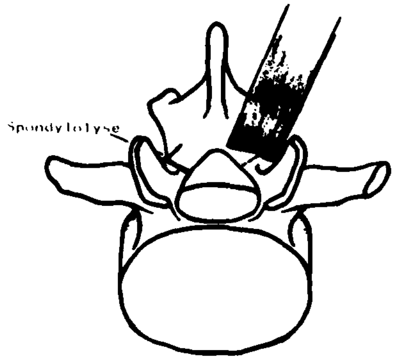


fig.12: Response of lumbar spine in vitro
reference point: os sacrum

In regard to this we conducted a total of 9 operative procedures to clairify whether these would alter the response. We performed a one-side dessection of the pars interarticularis at L 5. Here the operative situation and the x-ray to document the correct localisation of the spondylolysis is being shown. Afterwards the lysis was performed on both sides.

Results

A one-sided lysis had no apparant affect. Conversely the curve representing the change of the amplitude ratios shows a decline of increase at the side of the resonance for the double-sided spondylolysis up to a value of factor 0,5 (fig. 13/14).



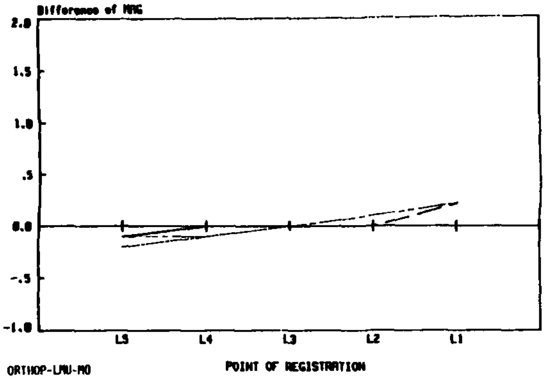


fig.13: Operation: artificial spondylolysis (L5-one side)

fig.14: Difference of frequency-response,operation-type: spondylolysis (L5-one side)

Next a spinal column segment is fused, as was done here in this experiment between L 4 and L 5 with a compression- or distraction spondylodesis. Compression at segment L 4 demonstrates a decrease to 0.5 and at L 2/L 1 a greater increase also of around the factor 0.5. The distraction even causes a stronger increase up to a factor of 1.0 onward from L 3. This implies an increase of the amplitude ratio possibly up to 40 % that means an increased strain on these segments (fig. 15/16).

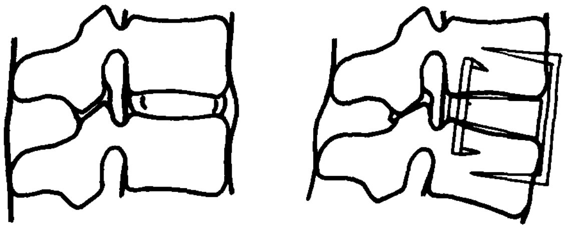


fig. 15: Operation: artificial distraction-spondylodesis

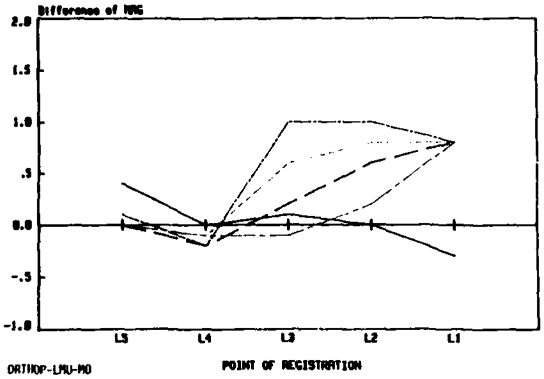


fig.16: *Difference of frequency response*
Operationtype: distraction-spondylodesis

The following deductions can be made:
Throught the set-up of the tests it was possible to *simulate* in the experiment the in vivo measured response, since the resonance values for the spinal column also resulted to lie between 6-10 Hz. Fusions cause an increase of the amplitudes within the neighbouring segments and therefore impose an increased strain.

Conclusions

The human spinal column acts as a vibration system with attached masses when exposed to forced vibration. The spinal column has the potential *to absorb*. Of the 3 demonstrated resonance areas 4-5 Hz corresponds with the entire body and the area between 7-10 Hz represents the spinal column. The resonance at about 18 Hz can be representative for the head.

The absorption of the *spinal column* causes a decrease at the head up to 40 %.

Rigid segments like the pelvis or the thoracic spinal column as well as operative induced fusions cause a build-up of vibrations in the resonance area at the neighbouring segments. Therefore, these areas are exposed to an increased amount of strain and are most likely subject to degenerative changes. The development of the set-up of reproducable conditions for in vitro examinations of spinal response to sinusoidal G_z-vibration was achieved. The experimental set-up enables the possibility to examine further questions.

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DISCUSSION

SANDOVER, UK: I'd like to congratulate both authors (Papers Nos. 16 and 17) on the very difficult pieces of work they are doing. Those of us involved with ordinary measurements of vibration transmissibility from the outside find it bad enough; but when you start getting onto the vertebrae, it is very very difficult indeed. Professor Dupuis showed some time ago that there is a lot of bending at the vertebrae, and I wonder how you took this into account. From the description here, you assumed that the vertebrae were moving in one direction. Were you able to correct for the actual rotational motion of the vertebrae?

HAGENA, GE: I described this method of measurement about two years ago, when I indicated that I only measured it in the one direction. I didn't measure the rotational component, or the horizontal component; only the Gz component.

WILDER, US: I'd also like to congratulate you on a very nice piece of work. Did you happen to notice any effect of the local anasthesia on the response? I presume that might have been difficult since the control for that type of observation would have to be unanesthetized.

HAGENA, GE: I can only add that I was the first person to have undergone this experiment. I fell asleep on the shake table and the people around me cried out: "What happened?", because some of the responses on the T.V. were not quite right; so I woke up and we started over again. It shows that there must be some muscle support to maintain the position. We got reproducible results, and we also assumed some experimental positions two or three times to see if it was possible to replicate them. I have to say, though, that I should have averaged the results as there are individual changes between subjects.

LANDOLT, CA: Have you any explanation as to why Andersson (Paper No. 17) did not get the resonance peak at 7-10 Hz that you did? Also, when you found that up to 40% of vibration was absorbed from the sacrum to the head, was that in reference to standing or sitting positions, or both?

HAGENA, GE: I do not have an explanation for why Andersson did not find this particular resonance. The absorption of vibration was in reference to both standing and sitting.

WILDER, US: I didn't notice it on the schematic of your shaker, but did you also shake the feet? Was the seat unit on which the subjects were sitting attached to a foot-support unit? I know that Andersson's unit did have a foot support.

HAGENA, GE: I didn't have a foot support.

WILDER, US: That may have introduced a rotational vibration in the lower limbs.

HAGENA, GE: The sitting positions in our experiments were stable. We had a fixed support on the table, or had a free-standing support; and there were only differences when we had a free-standing support, because, in some manner, waves were introduced through the ribs.

IN VIVO MEASUREMENTS OF VIBRATION TRANSMISSION IN THE HUMAN SPINE

(An Abstract)

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Lars Jorneus, M.S.
Erik Hult, M.S.

Although conclusive evidence does not exist, there are many epidemiological surveys suggesting an increase risk of low back pain in persons exposed to vibrations. Theoretical calculations indicate that spinal motion segment components can be stressed by whole body vibration exposure to the degree that fatigue failure can occur. Further, it is also known that vibration can interfere with disc nutrition.

Several studies have been published in which the response of the trunk as a whole to vibration was measured. These measurements were usually made with a single uniaxial accelerometer placed on the head of the subject or at some place on the surface of the trunk. The output accelerations have then been related to the input, i.e., vibration transfer functions have been calculated. In this paper we report on *in vivo* experiments in which vibration was measured in the three principal directions *in the* sagittal plane with accelerometers attached directly to lumbar vertebrae in human volunteers.

MATERIALS AND METHODS

The study was performed on five healthy volunteers. The vibration exposure was provided using a special vibration exciter that is based on a resonating system. Using this exciter the subjects were vibrated when sitting with sinusoidal vertical accelerations of 0.1g and 0.3g (0.98 and 2.94 m/s^2) in a frequency range from 2 to 15 Hz. Vibration along the spine was measured at three different points, two lumbar vertebrae and the sacrum. Measurements were made with the plane motion acceleration transducer (PAT), consisting of three linear accelerometers mounted in a special configuration on an aluminum fixture. The transducer was mounted on a K-wire which was inserted into the spinous processes and the sacrum. The PAT accelerometer measurements were validated using several fresh cadaveric functional spinal units mounted on an electro-mechanical vibrator.

The vibration amplitude, which was measured by an accelerometer placed on the seat, was kept constant while the frequency was varied in several steps from 2-15 Hz. At each step, ings were made for about 30 s. The output from each PAT was transformed to its corresponding vertebral body. This was done using a mathematical model with the help of measurements taken from lateral photographs of each subjects as well as a lateral x-ray of the spine. Transfer functions were then calculated and defined as the ratio of the vertebral or sacral acceleration in a given direction to the vertical seat acceleration. Rms-values were used in all analyses. Temporal relationships between the vertebral acceleration and the seat acceleration were documented by measurements of the phase angle. The subjects were sitting directly on a force plate and thus the vertical force between the seat and the subject was also plotted as a function of the frequency.

RESULTS

The vertical acceleration transfer functions for the five subjects were quite similar. They reached a peak value of about 1.6 at about 4.5 Hz, and decreased to about 0.5 at 7 Hz and then remained constant for the rest of the observed frequency range. The transfer functions for the horizontal accelerations increased from about 0.2 to the maximum of 0.8. There was no resonance along the horizontal translation within the frequency range studied. Transfer functions for the rotatory accelerations show significant variation in response between subjects. The curves appear to peak at about 5 Hz, close to the resonance frequency for the vertical acceleration.

The phase angle for the vertical acceleration was throughout negative indicating that the vertebral acceleration lags behind the seat acceleration. The curves start at zero value and decrease to about -60 degrees at about 6 Hz, and then slowly increase. Force measured from the force plate and plotted versus frequency yielded curves that were similar to those for the vertical vertebral transfer functions.

Accelerations measured at the two vertebral levels (L1 and L3) did not differ significantly. There was no significant difference in the system response for 0.1g and 0.3g inputs.

CONCLUSIONS

Pure vertical sinusoidal input to the body produces vibrations of the lumbar vertebrae that are not only vertical but also horizontal and rotatory. The resonance frequency of the lumbar vertebrae in the vertical direction was 4.5 Hz, in the horizontal direction beyond the upper limit of the experiment, and for the rotatory motion it was 5 Hz.

ACKNOWLEDGEMENTS

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COMMANDE NUMERIQUE D'UN POT VIBRANT
POUR L'ETUDE DES SIGNAUX TRANSITOIRES EN BIOMECANIQUE

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RESUME

Afin d'étudier la propagation d'un choc mécanique appliqué sur la colonne vertébrale d'un primate bioinstrumenté, les auteurs ont développé un système de commande numérique du signal de choc. Disposant d'un accéléromètre implanté, il est possible d'imposer, au point d'implantation, une forme temporelle d'accélération choisie par l'expérimentateur. L'excitation mécanique est effectuée à l'aide d'un pot vibrant électrodynamique sur lequel est fixé la base du siège de contention de l'animal. Le signal électrique envoyé sur le pot vibrant est calculé numériquement par un miniordinateur.

Le système calcule un filtre compensant exactement les caractéristiques du système générateur de vibration. Il tient également compte des caractéristiques dynamiques de la structure biologique.

Cette technique repose sur l'hypothèse de linéarité et d'invariance dans le temps de la structure biologique. Toutefois, l'invariance dans le temps n'est nécessaire que sur des intervalles de temps brefs. De même, du fait de l'algorithme rétroactif utilisé, une parfaite linéarité n'est pas nécessaire.

La méthode, ses limites et les moyens mis en oeuvre sont exposés. Les résultats obtenus sont rapportés.

INTRODUCTION

Le but du travail présenté est de mettre au point un système susceptible de permettre l'application à une structure biologique - dans le cas d'espèce une colonne vertébrale de primate - une excitation représentée par un signal transitoire, à transmission solidienne, parfaitement connu et parfaitement reproductible, en particulier sur la forme d'onde.

L'intérêt de ce travail se développe tant au plan de la physiologie fondamentale, qu'au plan de la physiologie appliquée à l'ergonomie aéronautique ou plus généralement à l'ergonomie des moyens de transport.

Intérêt en physiologie fondamentale parcequ'il est indispensable, pour caractériser le comportement dynamique d'une structure, d'en connaître sa réponse impulsionnelle. Les résultats obtenus lorsqu'un choc est appliqué au niveau du sacrum, par l'intermédiaire d'une broche vissée sur la face antérieure de la vertèbre, ont été présentés à la réunion Agard qui s'est tenue à Cologne en avril 1982 (1). Le travail que nous rapportons aujourd'hui est une étape supplémentaire puisqu'elle nous permet d'appliquer le choc par voie externe.

Intérêt également en physiologie appliquée puisque nous sommes maintenant en mesure, grâce au système que nous avons développé, d'appliquer aux individus des signaux recueillis sur le site. Il s'agit évidemment des facteurs d'agression physique de l'environnement - chocs, impacts et vibrations - transmis aux individus au cours de déplacements de véhicules, de transports, ou de combats, aériens ou terrestres.

I - POSITION DU PROBLEME

1.1 - CHOIX DU SIMULATEUR

Il existe diverses sortes de machines d'essai au choc, c'est-à-dire de dispositifs destinés à soumettre un système à des chocs mécaniques commandés et reproductibles. La norme NF E 90-001 n° 328 distingue une dizaine de types de machines. Parmi celles-ci se trouvent les systèmes à action purement mécanique : gravité, ressort, plan incliné, etc... Ces systèmes donnent des formes temporelles (profils) d'accélération reproductibles mais imposées par construction et de forme simple. Par contre, lorsque l'on désire reproduire avec précision la forme temporelle d'un signal d'accélération quelconque, seuls les systèmes hydrauliques ou électrodynamiques peuvent convenir car il est possible de moduler électriquement les forces dynamiques exercées par l'excitateur sur la structure testée.

Le C.E.R.M.A. dispose d'un pot vibrant électrodynamique de marque Bruel et Kjaer constitué d'un corps d'excitation type 4802T associé à une tête d'excitation 4818 et à un amplificateur 2708.

1.1.1 - Principe de fonctionnement d'un pot vibrant électrodynamique

Un pot vibrant électrodynamique comprend schématiquement (figure 1) :

- un corps d'excitation créant un champ magnétique (B) à l'aide d'un courant continu circulant dans une (ou deux) bobines,
- une tête d'excitation, interchangeable, constituée d'une table permettant de fixer la structure à tester, d'une suspension et d'une bobine mobile se déplaçant dans l'entrefer du corps d'excitation. La bobine est parcourue par un courant de commande (I) issu d'un amplificateur de puissance.

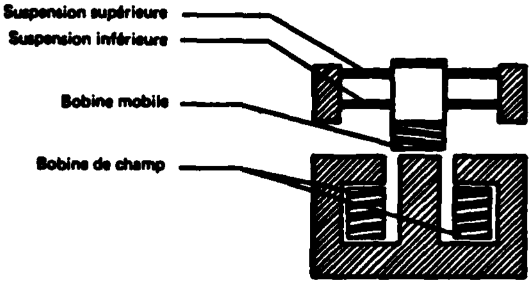


Figure 1 : Principe de construction d'un pot vibrant électrodynamique

La force créée est donnée par la loi de Laplace :

F = B.I.l

où F est la force en Newton
B l'induction magnétique en Tesla (ou weber/m)
I le courant en ampère
et l la longueur du fil constituant la bobine mobile.

- un amplificateur de puissance : celui-ci peut fonctionner selon deux modes :

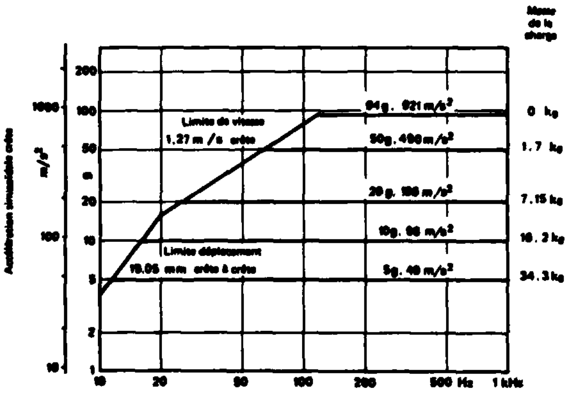
. en générateur de tension. La grandeur imposée à la structure testée est la vitesse ou les grandeurs proportionnelles : accélération et déplacement.
. en générateur de courant. La grandeur imposée est alors la force (F = BIl).

Un tel transducteur (avec son électronique associée) présente l'avantage d'être sensiblement linéaire en amplitude. Par contre, sa réponse en fréquence est complexe du fait de phénomènes de résonance et de l'interaction avec la structure soumise aux vibrations. Une mise en forme du signal de commande est donc nécessaire pour exploiter au mieux les possibilités du transducteur.

1.1.2 - Caractéristiques du pot vibrant

Les caractéristiques principales sont les suivantes :

- force maximale développée : 1780 N.
- Déplacement maximal 0,75 inch soit 19 mm crète à crète.
- Vitesse maximale 1,27 m/s.
- Masse de l'élément mobile 1,93 kg.
- Puissance fournie par l'amplificateur 1200 VA sur 0,6 Ω.



Performance sinusoïdale de la tête d'excitation B et K 4818.

Figure 2

Ces limitations sont rassemblées sur un schéma (figure 2) présentant les caractéristiques dynamiques (en régime sinusoïdal) du pot vibrant. En très basse fréquence (fréquence inférieure à 20 Hz), le déplacement maximal autorisé limite l'accélération disponible ($\gamma = \omega^2 x$). Au delà de 20 Hz, la limitation provient de la vitesse. Plus haut encore en fréquence, la force disponible limite l'ac-célération (1780/1.93 = 94 g pour une table nue). Le système (masse 250 kg) est monté sur une masse sismique (4 tonnes). La consommation de l'installation est d'environ 7 kVA.

1.1.3 - Essai en transitoire

Il s'agit de reproduire, non pas simplement le spectre fréquentiel d'amplitude d'un signal, mais également la forme temporelle du signal. Une batterie de filtres passe bande permettrait simplement d'obtenir un signal mécanique dont le module du spectre aurait la forme demandée. Mais la forme temporelle ne peut être obtenue ainsi, car cette technique ignore les caractéristiques de phase des filtres.

La solution est de remplacer la batterie de filtres par un seul filtre compensant exactement, en module et en phase, les caractéristiques fréquentielles du pot vibrant et de la structure testée. Seule une réalisation numérique de ce filtre permet de parfaitement contrôler non seulement le module, mais également la phase.

Si le spectre d'amplitude d'un signal est une notion bien connue, ce n'est pas le cas pour le spectre de phase. Et pourtant, la moitié de l'information concernant le signal y est contenue. Ainsi, dans un système numérique d'analyse de Fourier, si la fonction f(t) est connue en N points, le spectre d'amplitude est connu sur N/2 points. Le spectre de phase est également connu en N/2 points.

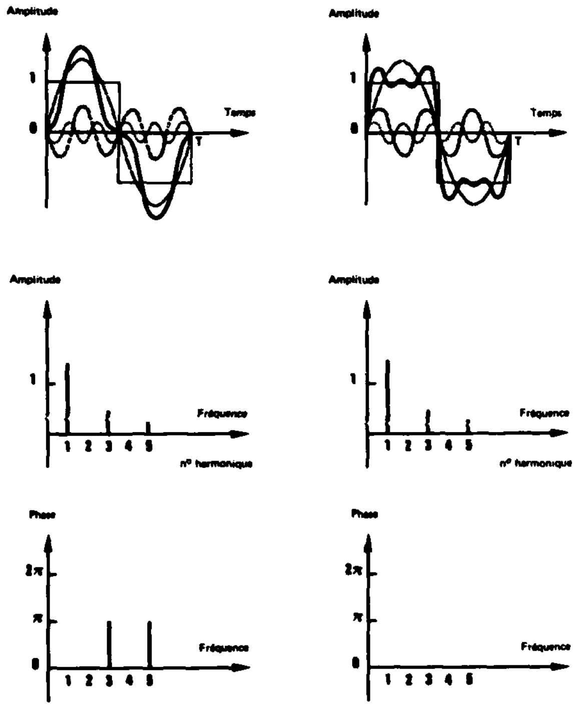


Figure 3. – Représentation temporelle de deux signaux ayant la même composition harmonique, mais des spectres de phase différents.

La figure 3 présente deux signaux périodiques ayant le même spectre d'amplitude. Les spectres de phase sont différents. Les formes temporelles des signaux sont profondément différentes.

L'importance d'un contrôle rigoureux du module et de la phase du filtre à interposer pour mettre en forme le signal d'excitation étant ainsi établie, il nous reste à comparer les réponses obtenues en régime transitoire avec et sans filtrage numérique.

La figure 4 présente un exemple de reproduction d'un signal en dent de scie. Ce signal provient d'un générateur électrique (figure 4a). Au travers de l'amplificateur de puissance, le signal est envoyé sur le pot vibrant.
La figure 4b présente l'accélération mesurée sur le pot vibrant. Le signal reproduit est déformé. Il a perdu sa symétrie temporelle, la crête négative est deux fois plus importante que la crête positive, il y a apparition d'une oscillation parasite lentement décroissante.
La figure 4c présente l'accélération (même pot vibrant !) obtenue après mise en forme, par traitement numérique, du signal de commande. Cette fois, l'accélération recueillie a la même forme que le signal à reproduire. On notera toutefois la présence d'un léger bruit présent sur toute la durée du signal.

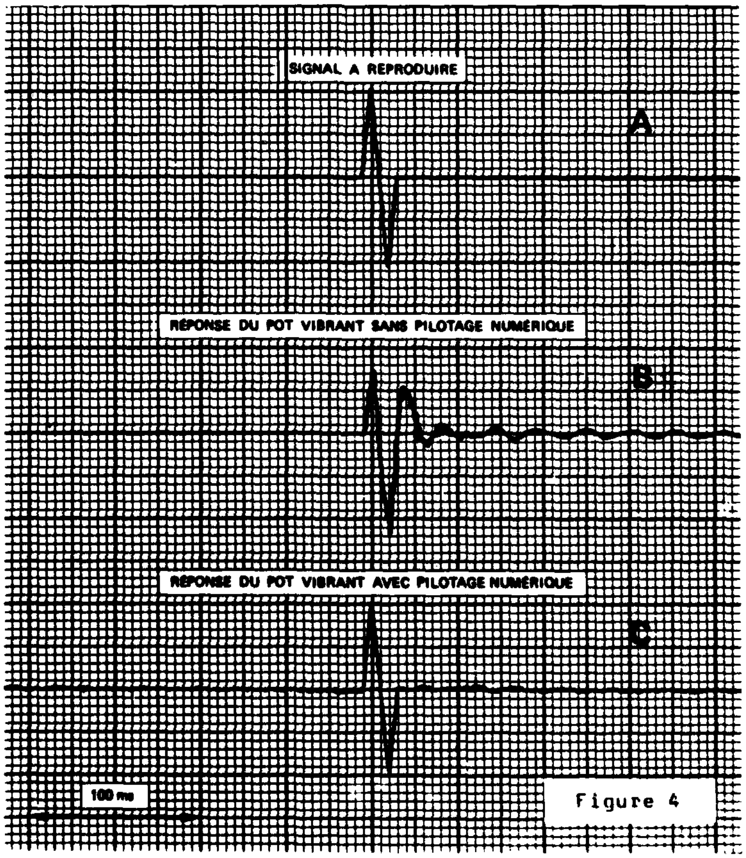


Figure 4

II - COMMANDE NUMERIQUE : PRINCIPE - LIMITES - SYSTEME DE TRAITEMENT MIS EN OEUVRE

2.1 - FONCTION DE TRANSFERT DU POT VIBRANT

Le pot vibrant peut être modélisé sous forme d'une "boîte noire" présentant une entrée (tension électrique e(t)) et une sortie (accélération $\gamma(t)$ de la table vibrante).

$$e(t) \longrightarrow \boxed{h(t)} \longrightarrow \gamma(t)$$

Si h(t) est la réponse impulsionnelle du pot vibrant, la relation existant entre l'entrée et la sortie est :

$$\gamma(t) = \int_{-\infty}^{+\infty} h(t-\tau)\, e(\tau)\, d\tau \qquad 1$$

c'est-à-dire : $\gamma(t) = h(t) * e(t)$

ou * est le produit de convolution.

Cette équation se simplifie lorsque l'on passe dans le domaine fréquentiel.

$$\gamma(f) = H(f) \times e(f)$$

e (f) et $\gamma(f)$ sont les transformées de fourier et e (t) et $\gamma(t)$

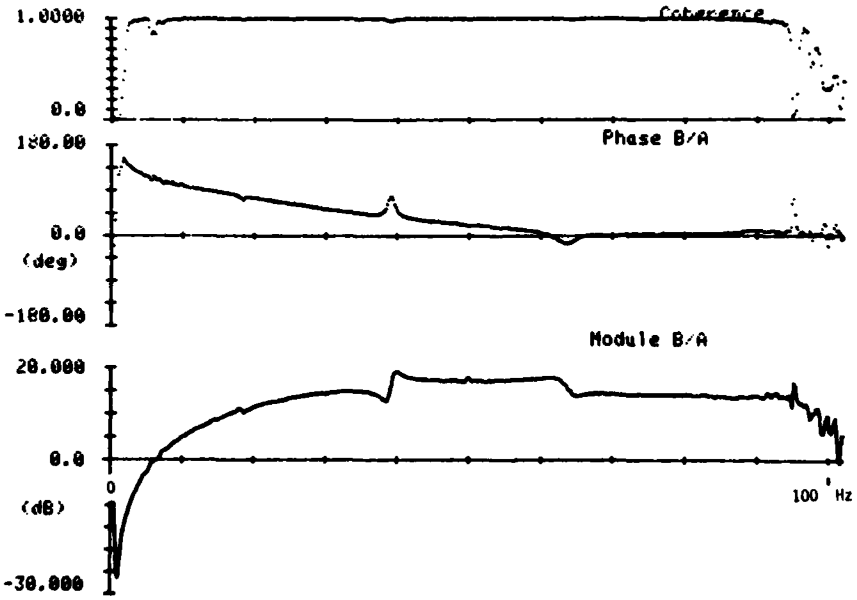
$H(f) = \dfrac{\gamma(f)}{e(f)}$ est la fonction de transfert du pot vibrant

e (f), $\gamma(f)$ et H (f) sont des nombres complexes.

En régime sinusoïdal, le module de H(f) est égal au rapport des amplitudes de l'accélération par la tension. La phase de H (f) est égale au déphasage existant entre l'accélération et la tension.

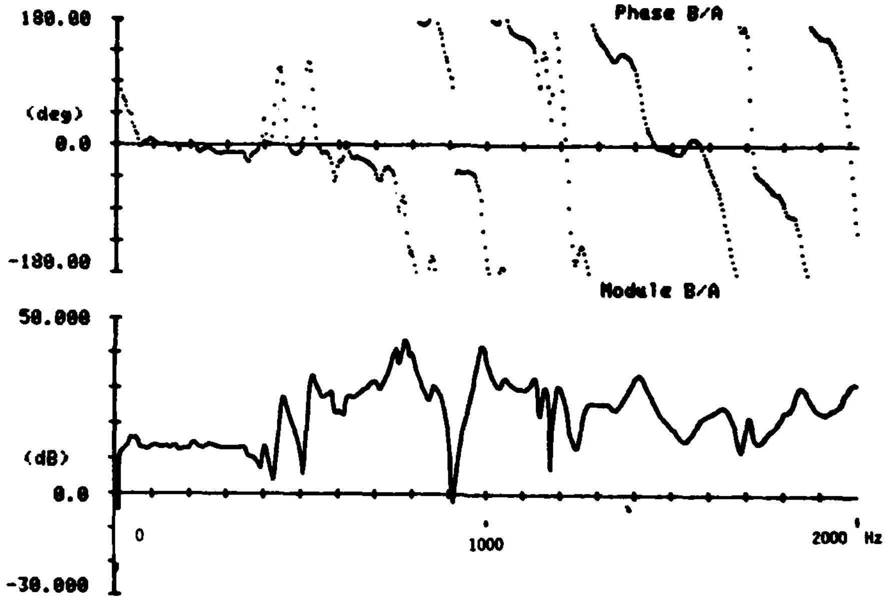
La théorie mathématique est très puissante car la relation 1 est valable quelle que soit l'excitation e. Celle-ci n'a pas besoin d'être sinusoïdale.

Les figures 5 et 6 présentent un exemple de fonction de transfert du pot vibrant. Sur la figure 5 ramenés en abscisse à une bande d'analyse 0-100 Hertz on lit en bas les variations du module en décibel $n = 20 \log \frac{\gamma}{e}$, au centre les variations du déphasage en degrés, en haut la valeur de la fonction de cohérence. Cette dernière dont la valeur est nécessairement comprise entre 0 et 1 renseigne sur la qualité de la mesure (rapport signal sur bruit) ainsi que sur la linéarité de la structure testée. On voit que les courbes de module et de phase sont très régulières. Ce n'est pas le cas sur la figure 6 où le domaine de fréquence analysé s'étend jusqu'à 2000 Hz.



FONCTION DE TRANSFERT DU POT VIBRANT (AVEC CHARGE)

Figure 5



FONCTION DE TRANSFERT DU POT VIBRANT (AVEC CHARGE)

Figure 6

2.2 - PRINCIPE DE LA COMMANDE

Le problème de la commande numérique en régime transitoire peut s'énoncer ainsi :

Quel signal faut-il appliquer à l'entrée du pot vibrant pour obtenir une accélération donnée ?

La *réponse* est immédiate dans le domaine fréquentiel :

$$e(f) = \frac{\gamma(f)}{H(f)}$$

Pour revenir au domaine temporel, il faut calculer la transformée de Fourier inverse des deux membres.

Il vient : $$e(t) = \overline{\mathcal{F}}\left[\frac{1}{H(f)} \times \gamma(f)\right]$$

La méthode nécessite donc les calculs suivants (figure 7) :

- transformée de Fourier du signal d'accélération désiré,
- détermination de la fonction de transfert,
- multiplication de la fonction de transfert,
- multiplication dans le domaine fréquentiel de $\frac{1}{H(f)}$ par $\gamma(f)$
- transformée de Fourier inverse.

Tous ces calculs ne peuvent être effectués qu'après numérisation des signaux. Un retour en analogique est évidemment nécessaire pour attaquer le pot vibrant.

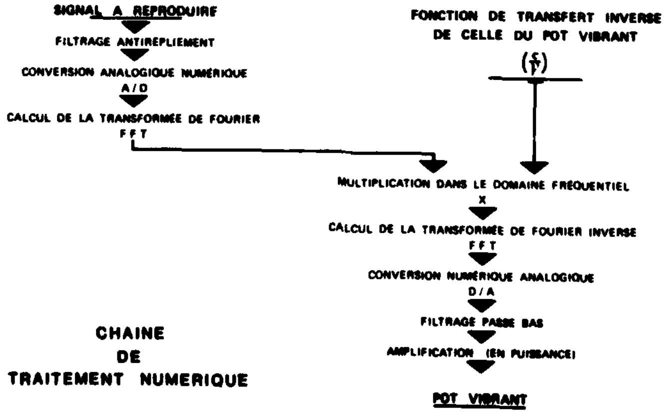


Figure 7

2.3 - LES LIMITES

Elles sont de deux sortes :

- mécaniques, ce sont les limites du pot vibrant lui-même : déplacement maximal, vitesse maximale, etc... Ceci a été abordé au paragraphe 1.1.2.

- Mathématiques, le système physique doit être continu, invariant dans le temps et linéaire. Ces trois conditions sont nécessaires pour que le système puisse être décrit par un opérateur de convolution. Si pratiquement tous les systèmes physiques sont continus, il n'y a aucune raison pour que la structure soit invariante et linéaire.

2.3.1 - Invariance temporelle

Il s'agit de l'invariance des caractéristiques du système. Au cas où celle-ci ne serait pas vérifiée, il est toutefois possible d'adapter la méthode au cas où les variations sont lentes. Il suffit de prendre en compte l'évolution de la fonction de transfert au moyen d'estimations répétées dans le temps. La variation sera considérée comme lente si elle est du même ordre que le temps de boucle du système (temps nécessaire pour calculer la nouvelle fonction de transfert et élaborer le nouveau signal de commande).
L'évolution temporelle de la fonction de transfert peut être due à l'échauffement de certaines parties du système, éventuellement à son usure, voire sa rupture. Dans le cadre d'une expérimentation animale, l'évolution peut être due à une modification de la raideur ou de la posture du sujet d'expérience.

2.3.2 - Linéarité

La linéarité en question est celle du pot lui-même et également celle de la structure testée. N'importe quel système physique a un domaine de linéarité limité. Un simple ressort élastique très fortement étiré voit sa raideur se modifier.

Mathématiquement, la fonction de transfert d'un système non linéaire n'existe pas. Physiquement, on peut pourtant approcher un tel système par une fonction de transfert représentant une approximation linéaire d'un phénomène non linéaire. La fonction de transfert est alors appelée fonction de transfert cohérente. Une telle technique associée à une mise à jour de l'estimation au cours de l'augmentation des niveaux d'excitation, permet d'obtenir de bons résultats sur des systèmes faiblement non linéaires. Toutefois ceci se fait en utilisant une méthode prenant beaucoup de temps de calcul. Cela impose également des contraintes méthodologiques qui sont exposées dans le chapitre III.

2.4 - LE SYSTEME DE TRAITEMENT NUMERIQUE

Le système développé au C.E.R.M.A. est organisé autour d'un mini-ordinateur 16 bits PDP 11 34 de chez Digital Equipement (DEC) pilotant un analyseur de spectres bivoies SD 360 de chez Spectral Dynamics.

2.4.1 - Le mini-ordinateur PDP 11-34 et son système

Le système est principalement constitué d'unités de disque, de disquette, d'une imprimante et d'une console de visualisation. La mémoire centrale est de 256 kilooctets, il existe une carte de calcul en virgule flottante. On dispose d'une carte de conversion numérique analogique et analogique numérique 12 bits ainsi que d'une carte interface IEEE 488.

Un système appelé "atténuateur et relais programmable" a été développé autour d'une carte interface Spectral Dynamics 13209 pour exploiter la pleine dynamique (12 bits) du convertisseur numérique analogique attaquant l'amplificateur du pot vibrant. Les relais programmables permettent des sécurités empêchant d'appliquer un signal au pot vibrant, en dehors des intervalles de pilotage. Ils permettent également l'établissement automatique du cablage.

2.4.2 - Analyseur de Spectre - Spectral Dynamics SD 360

Cet analyseur de Fourier, deux voies, travaille en temps réel jusqu'à 15 kHz. Il possède deux mémoires d'entrée de 1024 points chacune. L'appareil permet, notamment, le calcul des transformées de Fourier directes (Technique FFT), ou inverses, ainsi que le calcul des fonctions de transfert. L'analyseur est équipé de deux convertisseurs analogiques numériques 12 bits. On peut également y entrer directement en numérique, tous les échanges d'informations entre l'ordinateur et l'analyseur de spectres sont possibles.

III - REALISATION DU SYSTEME DE COMMANDE

3.1 - Détermination de la première fonction de transfert caractérisant le pot vibrant et la structure à tester

Il s'agit de déterminer le plus précisémment possible, la fonction de transfert. Si celle-ci est légèrement bruitée, le signal de commande risque d'être complément perturbé puisqu'il est obtenu par une opération de déconvolution. Cette détermination est ainsi un point critique de la méthode.

3.1.1 - Les divers types d'excitation

Il existe de nombreuses possibilités pour le choix du signal d'excitation : balayage sinusoïdal, impulsion, aléatoire. De toutes façon, le comportement du pot, ni celui de la structure à tester, n'étant pas connus, le signal d'excitation doit avoir un spectre d'amplitude constant dans la bande de fréquence étudiée.

- L'utilisation d'un balayage sinusoïdal est la méthode la plus précise pour les systèmes linéaires. Elle n'est toutefois pas facile à mettre en jeu sur ordinateur et elle est très longue.

- La méthode impulsionnelle, par contre, est très rapide. Elle n'est pas adaptée s'il y a des non linéarités, car celles-ci sont alors excitées à coup sûr. D'une façon plus générale, le rapport signal sur bruit obtenu est médiocre car il n'y a que très peu d'énergie mise en jeu.

- L'excitation aléatoire est très séduisante. Rapide et peu sensible aux non linéarités, elle est toutefois très difficile à mettre en oeuvre sur ordinateur. Elle nécessite en effet de nombreux brassages de données.

- L'excitation pseudoaléaléatoire est facile à mettre en oeuvre. Son utilisation est encore plus rapide. Quoique moins adaptée aux systèmes non linéaires, cette technique est celle retenue pour notre système de commande.

3.1.2 - Excitation pseudoaléatoire : génération et intérêt

Cette technique d'excitation est appelée à "variance nulle" ou SSG (synchronous signal generation).

Le signal est d'abord généré dans le domaine fréquentiel. Un spectre fréquentiel d'amplitude constante est défini (bruit blanc). Les phases de chaque composante fréquentielle (spectre de phase) sont choisies aléatoirement entre 0° et 360 degrés. Une transformée de Fourier inverse donne alors le signal temporel. La séquence ainsi créée est reproduite périodiquement. Le signal analogique est obtenu après passage à travers un filtre passe bas. L'histogramme d'amplitude obtenu n'est pas parfaitement Gaussien. Il présente une certaine structure fine (figure 8).

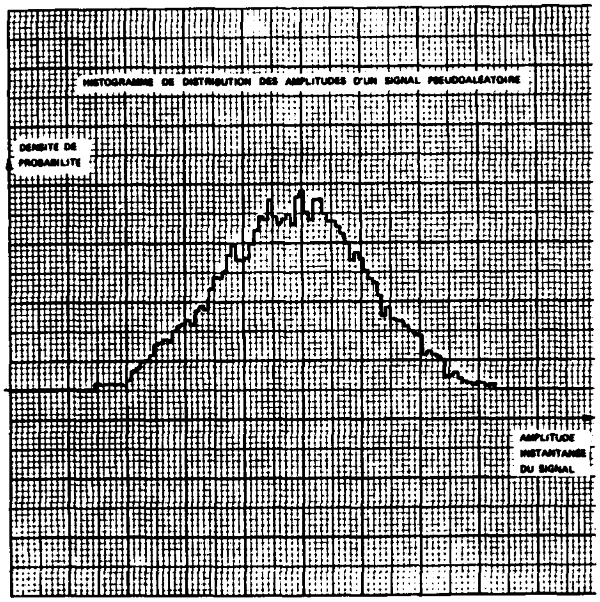


Figure 8

Si la séquence était répétée indéfiniment, son spectre ne contiendrait de l'énergie que pour les points du domaine fréquentiel qui sont contenus dans la version échantillonée initiale. Pour s'approcher de ce cas, il suffit de répéter le signal de telle sorte que sa durée totale soit nettement supérieure (facteur 10 par exemple) à la plus longue période contenue dans la version échantillonnée.

L'analyse des signaux d'excitation (pseudo aléatoire) et de réponse de la structure, se fait à la cadence du convertisseur digital analogique. Cette synchronisation permet le parfait calage des fréquences analysées sur les fréquences présentes dans les signaux.

L'estimation des fonctions de transfert est alors très rapide, du fait de l'excellent rapport signal sur bruit, à chaque fréquence. Les mesures moyennes portant sur de longues durées sont inutiles. Par ailleurs, si le signal périodique pseudoaléatoire est appliqué suffisamment longtemps, le système à tester est alors en régime permanent. Sa réponse est périodique et de même période que l'excitation. Il n'est plus nécessaire d'utiliser une fenêtre de pondération temporelle de type Hanning, destinée à limiter les effets de bord. La résolution spectrale en est alors améliorée.

Notons enfin que le calcul effectif de la fonction de transfert est effectué par l'analyseur bivoies Spectral Dynamics SD 360.

3.2 - ELABORATION DU SIGNAL DE COMMANDE

L'estimation initiale de la fonction de transfert permet d'élaborer une première impulsion de commande à l'aide de la relation

$$e(t) = \overline{\mathcal{F}}\left[\frac{1}{H(f)} \times \gamma(f) \right]$$

où $\gamma(f)$ est la transformée de Fourier de l'impulsion temporelle désirée (calcul effectué par l'analyseur spectral sur 2 X 512 points).

L'inversion de H (f) est évitée en estimant directement non pas H (f) mais 1/H(f). L'estimation de 1/H(f) est également effectuée en 2 X 512 points.

La multiplication dans le domaine fréquentiel est réalisée dans l'unité centrale du miniordinateur PDP 11-34. Le résultat est envoyé sur l'analyseur spectral qui effectue la transformée de Fourier inverse. L'impulsion temporelle calculée est renvoyée vers l'ordinateur. Elle est alors disponible aux bornes d'un convertisseur numérique analogique 12 bits et peut être également stockée sur un fichier disque, ainsi que la configuration de tout le système.

Il est possible de s'arrêter là dans l'élaboration du signal de commande. Après avoir traversé un filtre passe bas (Rockland 816 A) et un amplificateur à gain programmable (Réalisation CERMA), le signal est alors envoyé sur l'amplificateur de puissance, attaquant le pot vibrant.

Toutefois, l'expérience montre qu'il est possible d'élaborer un deuxième signal de commande, plus précis, en observant la réponse du pot vibrant excité à bas niveau, par le premier signal de commande. L'amélioration est alors due à l'affinement de la détermination de la fonction de transfert du pot vibrant.

3.3 - MISE A JOUR DE LA FONCTION DE TRANSFERT DU POT VIBRANT

Du fait de la précision nécessairement limitée des mesures, et de l'existence de non linéarités, aussi faibles soient elles, il est toujours intéressant d'affiner la fonction de transfert en la déterminant à l'aide de signaux aussi proches que possible, en amplitude et en fréquence, des signaux que l'on désire restituer :

Soit une excitation initiale pseudoaléatoire effectuée au même niveau d'amplitude quelle que soit la fréquence. Supposons, que la structure testée possède une antirésonance à la fréquence f0, le signal recueilli sur la structure est très faible. Il en résulte un mauvais rapport signal/bruit (S/B) d'où une mauvaise valeur de la cohérence puisque celle-ci mesure en particulier le rapport S/B.

Si le signal à synthétiser n'a pas d'énergie dans la bande centrée autour de f0, la synthèse n'est pas perturbée. Sinon, le signal élaboré est médiocre.

Dans le cas où la structure présente des nonlinéarités, celles-ci sont prises en compte par cette technique. Ainsi qu'il a été dit précédemment, la fonction de transfert d'un système non linéaire n'existe pas. On en calcule toutefois une approximation, celle-ci dépend de la nature de l'excitation. Il est donc important, alors, de calculer une fonction approchée dans les conditions où l'on doit s'en servir. C'est à dire avec une excitation proche de celle que l'on utilise pour le pilotage en régime transitoire. Si la non linéarité est très importante, la fonction de transfert est affinée en plusieurs tours de boucle, chaque tour correspondant à une augmentation du niveau de l'excitation.

Le système de commande développé permet donc d'observer, dans une phase préliminaire, la réponse de la structure à une excitation impulsionnelle de même forme spectrale que celle que l'on veut restituer, mais de plus bas niveau. Le premier signal de commande est alors envoyé à -20 dB du niveau du signal réel soit une atténuation par un facteur 10.

Une nouvelle fonction de transfert est calculée à l'aide de l'excitation impulsionnelle. En fait, on envoie 4 impulsions à bas niveau. Ceci est nécessaire pour calculer la fonction de cohérence correspondante (la cohérence calculée en l'absence de moyenne effectuée sur plusieurs signaux est mathématiquement égale à 1).

Une moyenne des deux fonctions de transfert est alors effectuée sous certaines conditions :

- si la cohérence de la deuxième fonction de transfert est inférieure à une valeur seuil choisie par l'opérateur, aucune moyenne n'est effectuée. La deuxième fonction de transfert n'est pas prise en compte. En effet, la première fonction est calculée avec une excitation possédant un spectre plat. Elle est donc à priori la plus digne de confiance car toutes les fréquences étaient excitées.
- Par contre, si la deuxième cohérence est supérieure au seuil et si la première est inférieure à ce seuil, la première fonction de transfert n'est pas prise en compte.
- enfin, si les deux cohérences sont supérieures au seuil, une moyenne des modules et des phases est effectuée. Tous ces calculs et tests sont effectués fréquence après fréquence. La moyenne peut être effectuée sur un nombre quelconque de fonctions de transfert. L'algorithme est bouclé. A chaque tour de boucle un nouveau signal de commande est élaboré à partir de la dernière fonction de transfert estimée par la moyenne décrite ci-dessus.

L'opérateur décide de la sortie de la boucle lorsqu'il estime satisfaisante la forme du signal de commande. Trois tours de boucle sont généralement suffisants. Le signal peut alors être envoyé à son niveau réel, la fonction de transfert étant stockée sur disque. Dans le cas ou le protocole expérimental permet l'envoi de plusieurs impulsions au niveau réel, la réponse de la structure est également prise en compte dans l'élaboration de la fonction de transfert.

Remarque

La moyenne calculée est du type exponentielle. Une telle moyenne permet la mise à jour de la fonction de transfert puisque le calcul est effectué en permanence. La constante de temps correspondante est à déterminer par l'opérateur. Si le système est linéaire et invariant dans le temps, les échantillons sont invariants et la fonction de transfert n'évolue pas.

3.4 - EXEMPLE DE FONCTIONNEMENT EN BOUCLE

Un exemple de l'amélioration de la qualité des signaux obtenus est présenté sur la figure 9.

A : signal d'accélération désiré

B : signal de commande calculé à partir de la fonction de transfert mesurée avec une excitation paseudoaléatoire. L'oscillation parasite de très basse fréquence résulte d'une mauvaise détermination de la fonction de transfert intitiale.

C : Réponse (en accélération) du pot vibrant

D : Nouveau signal de commande élaboré à partir d'une première mise à jour de la fonction de transfert prenant en compte la réponse de la lère impulsion de commande. L'oscillation parasite précédente est éliminée, mais il en apparaît une autre, sans doute masquée en b et c.

E : La réponse du pot vibrant s'améliore

F : Nouveau signal de commande. Les oscillations parasites ne sont plus visibles.

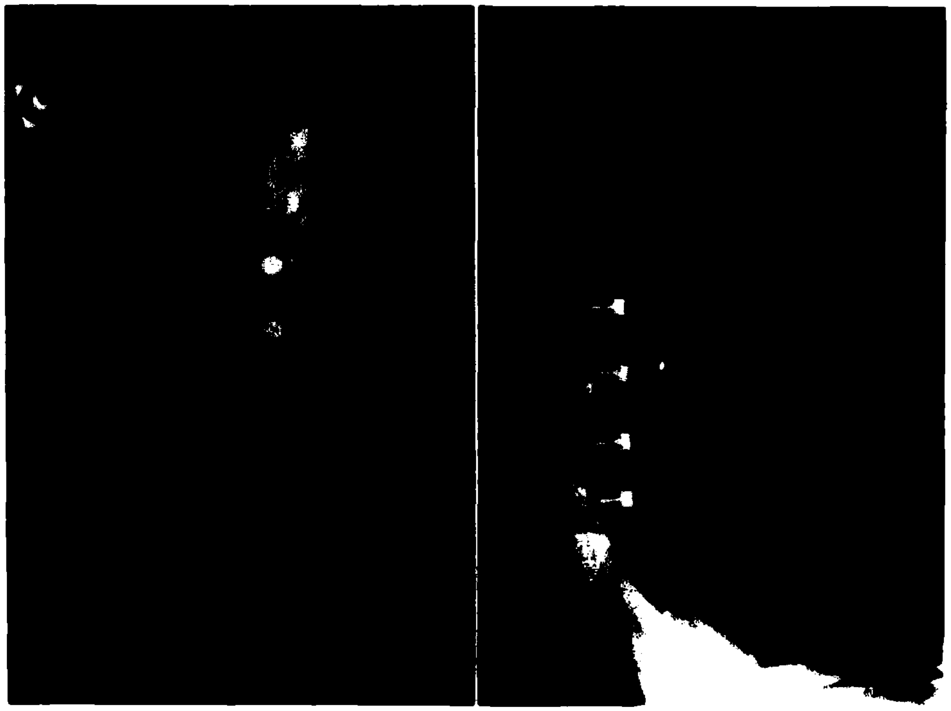
G : La réponse en accélération est améliorée. On ne s'attachera pas ici à l'amplitude du signal, celle-ci n'a été réglée qu'approximativement par l'opérateur. Le logiciel complet , développé pour l'étude, permet évidemment une calibration automatique en niveau.
Finalement, deux tours de boucle sont ici suffisants pour mettre en forme le signal.

IV - RESULTATS - DISCUSSION

Les résultats obtenus avec des structures mécaniques ont été présentés dans les paragraphes précédents (figures 4 et 9). Il reste à montrer la validité de la technique dans le cadre d'une expérimentation biomécanique.

Les résultats rapportés ici concernent des essais réalisés avec un babouin (masse 8 kg) assis dans un siège de contention fixé sur le pot vibrant. Les courbes du bas des figures 10 et 11 présentent les signaux que l'on désire reproduire. Les réponses respectives du pot vibrant (courbes du haut) sont mesurées au niveau de la base du siège de contention. L'animal est anesthésié. L'anesthésie associée à la contention permettent d'obtenir une structure biologique relativement invariante mécaniquement. En effet, un changement important de posture entrainerait des variations des paramètres mécaniques risquant de compromettre la synthèse des signaux.

Ce problème de l'invariance temporelle a déjà été abordé au paragraphe 2.3.1. Nous constatons ici que le résultat semble convenable.



Photos 1 et 2

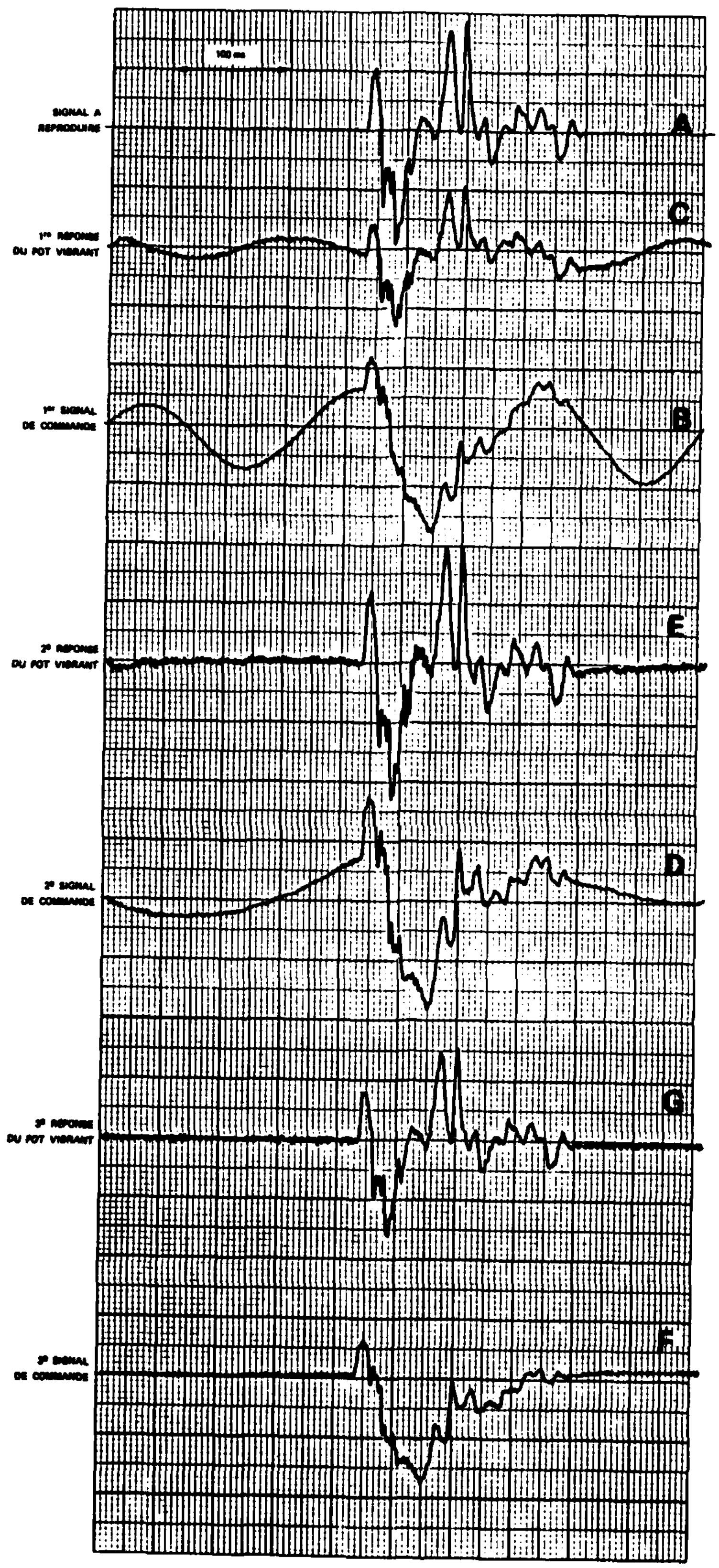


Figure 9

Exemple de fonctionnement en boucle

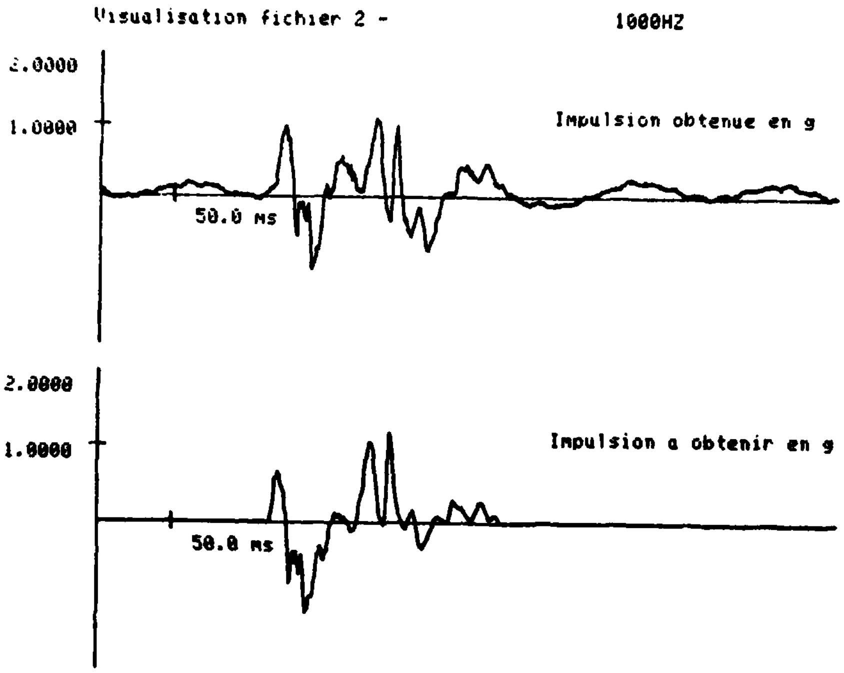


Figure 10

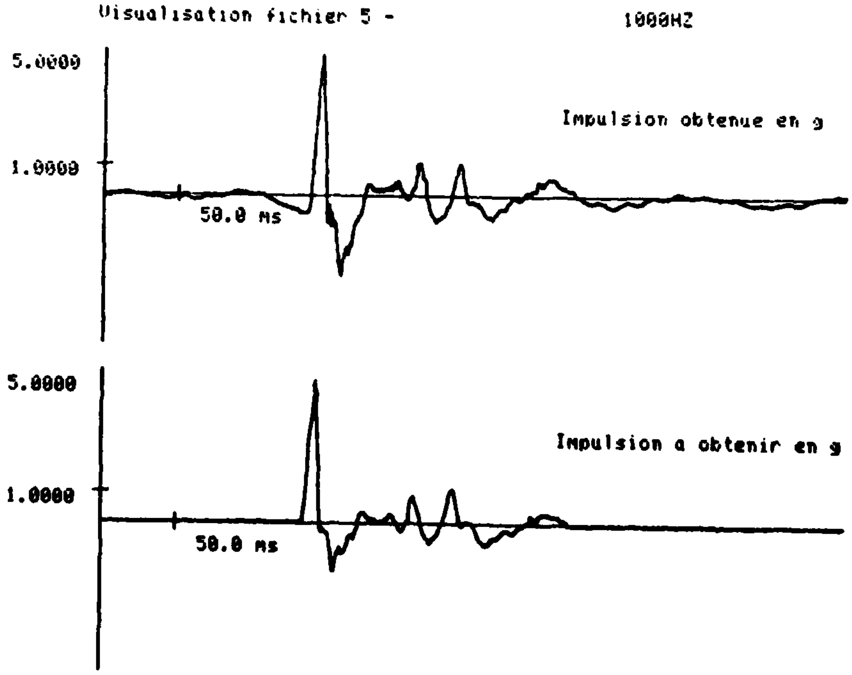


Figure 11

Les courbes du bas des figures 10 et 11 correspondent aux signaux d'accélération que l'on désire reproduire. Les courbes du haut présentent les accélérations recueillies sur la base du système de contention de l'animal.

Une deuxième série d'essai est réalisée en essayant de reproduire les mêmes signaux, cette fois, au niveau du sacrum d'un babouin profondément anesthésié. Le but est d'imposer une accélération de forme déterminée en un point de la colonne vertébrale. A cette fin, des accéléromètres miniatures sont implantés sur la colonne vertébrale lombaire de l'animal (photos 1,2). La technique d'implantation a fait l'objet de publications antérieures (2,3). Les résultats sont présentés sur les courbes 12 et 13.

CONCLUSION

Une technique numérique de traitement de signal a été développée afin de permettre le contrôle de la réponse transitoire d'une table vibrante chargée d'une structure biologique.

La reconstitution précise, en laboratoire, d'un environnement vibratoire réel est rendue faisable.

Dans le domaine de la biomécanique, et dans le cadre d'une expérimentation sur un babouin bioinstrumenté (implantation d'un accéléromètre), il est possible d'imposer, au point d'implantation, une forme temporelle d'accélération choisie par l'expérimentateur.

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AGARD CP 322 (6-1 6-21).

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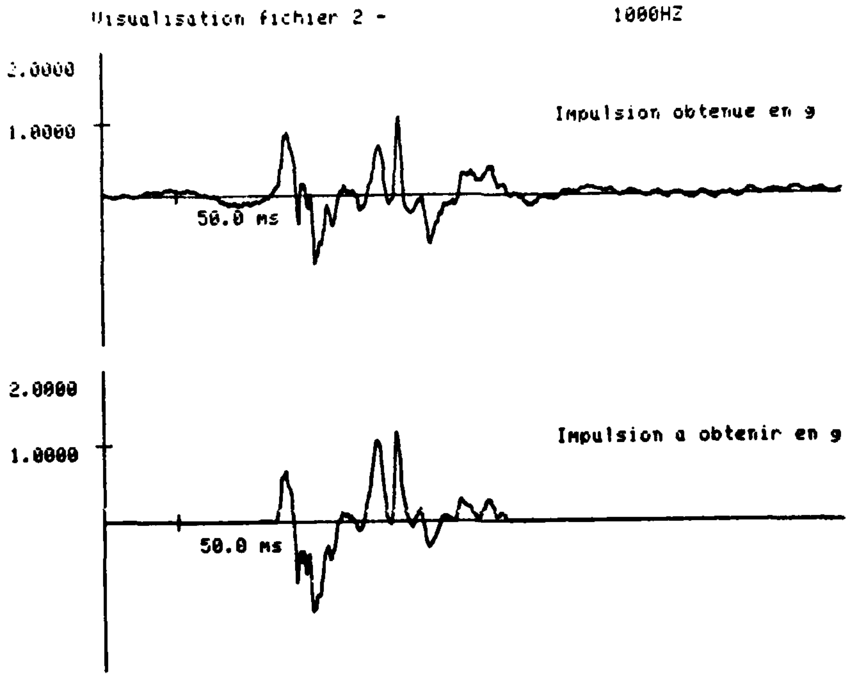

Figure 12

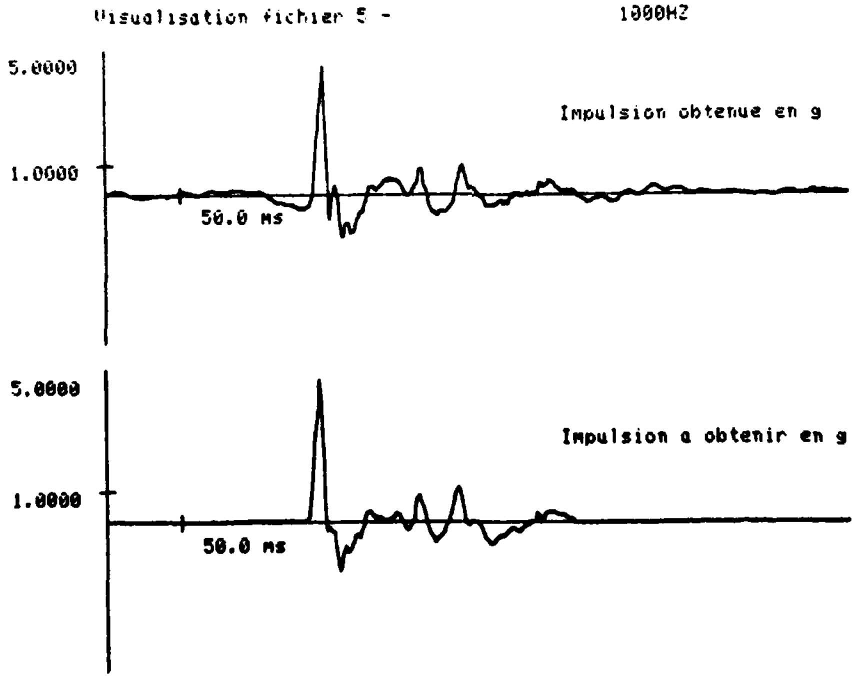

Figure 13

Les courbes du bas des figures 12 et 13 correspondent aux accélérations que l'on désire reproduire. Les courbes du haut correspondent aux accélérations recueillies sur le sacrum de l'animal.

PREDICTION OF LUMBAR SPINAL SEGMENT INSTABILITY BY CENTRODE PATTERNS

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SUMMARY:

The centre of rotation defines motion of the lumbar spinal segment. It is an indicator of spinal instability but since the motion segment does not move about a single axis, a locus of instantaneous axes of rotation or a centrode is defined. Centrodes in normal cadaveric spines as well as those with degenerative disc disease have been identified using moiré techniques as well as by computer analysis of small angles of motion. In this study 47 spines were assessed, 22 of which were evaluated with axial loading. The normal centrode lies within the posterior half of the disc space, averaging 22 mm in 10 specimens. In the earliest stages of degenerative disc disease the centrode lengthens significantly (average 116 mm). Moderate disc disease shifts the centrode inferiorly. Axial loading did not appear to influence the centrode lengths or position. The technique is highly sensitive detecting 94% of the abnormal spines as compared with only 25% detected by means of measuring excessive motion on flexion/extension radiographs. This method is a highly reliable and quantifiable method of detecting early changes in spinal motion in degenerative disc disease prior to the well recognized radiographic abnormalities.

(Key Words: spinal segment, degenerative disc disease, centrode).

The measurement of motion of human joints with small angular changes in rotation has been hampered by inaccuracies of the techniques used (1,2,3). Panjabi (4) has pointed out that measurements of the centres of rotation for small angles to date have been severely limited because of the large errors that result. Since the measurement of the centre of rotation has been the common method of defining angular rotation (2,3,5), the concept of instantaneous centres of rotation has been developed for the lumbar spine in order to define the accuracy of spinal motion (6). By identifying the centre of rotation for each 3 degree change in rotation for a lumbar spinal segment such as the L4-5 disc level, a series of centres is obtained. Joining these points defines a locus which can track the movement of this complex joint. This locus of centres of rotation is referred to as a centrode.

A technique derived from the use of moiré screens was initially employed to accurately measure centres of rotation for small degrees of motion in the lumbar spine (6,7,8). This method developed by Shoup (5) and modified according to the criteria of Panjabi (4) provides an accurate technique to locate the centres of rotation for small angular changes, since three lines of intersection are utilized, two of which meet at right angles. The technique was found to demonstrate a high degree of precision (reproducibility) and accuracy (6), that is, within 1.85 mm of the true centre for mechanical joints constructed with known centres of rotation and centrodes.

This method was applied to the L4-5 motion segment (7) to study patterns in the normal disc. Centrodes were produced which were located in or near the posterior third of the disc and moved in a direction from posterior to anterior and in some cases posterior again, as the spine flexed from full extension to full flexion.

The technique was further applied to cadaver spines with segmental instability secondary to degenerative disc disease (8). It was felt that by accurately measuring the degree of abnormal motion a better appreciation of instability of the motion segment could be obtained. Twenty-eight motion segments at the L4-5 level were classified into those which were normal and those which had minor, mild, moderate and severe radiographic evidence of degenerative disc disease. Using the moiré method it was found that there was a statistical difference in the length of the centrode between the normals and all other specimens with evidence of degenerative disc disease. The average length of the centrode for the normal group was 21 mm, whereas the remaining categories had centrode lengths as follows: minor - 127 mm, mild - 45 mm, moderate - 52 mm and severe - 29 mm. The moderate group had centrodes which were more inferior than the other groups.

Because of technical problems associated with the use of moiré techniques, a new method was devised to evaluate centrode patterns. This technique provides analysis of motion of the spinal segment by means of accurate markers and computer analysis. Specimens were examined both with and without axial loading.

Computer analysis has allowed the detection of centres of rotation for angles as small as 3 degrees and is more accurate since an accurate digitizer is utilized to check the position of the moving points (accurate to within 0.1 mm). All calculations are done arithmetically reducing geometric errors. Nine independent calculations for each centre of rotation can be done with the mean being taken to detect the average centre and the use of X Y co-ordinates reduces the overall error and allows for greater reducibility. For increased accuracy we followed four principles of measurement, as determined by Panjabi, to reduce error (4,10). This provided an accuracy of less than 1 mm distance from the true centre of rotation with 95% confidence at angles of rotation of approximately 3 degrees.

MATERIALS AND METHODS:

The L4-5 motion segment was obtained from 47 cadaveric spines under the age of 60 years. Metastatic disease or trauma excluded the specimens from testing. All soft tissues were removed except those maintaining the bone/ligament integrity. The spines were preserved at -70 degrees centigrade until ready for use. Each spine was graded for the degree of degenerative disc disease, both grossly and radiographically, and rated according to radiographic appearance. (Table 1). The spines were scored out of a maximum of 10 with normal being 0, minor degenerative disc disease having a score of 1-2, mild a score of 3, moderate 4-6 and severe 7 or greater. Discography allowed grading according to the description of Brown et al (11).

Prior to testing, the spines were thawed and mounted in a stainless steel assembly using dental acrylic cement and screws. Motion was studied in a specially constructed rig capable of moving the joints in a constant fashion by means of a motorized pulley system (7). Non-porous plastic wrap was used to maintain the humidity around the specimen.

Loading was designed to allow motion in the sagittal plane limiting lateral motion. Axial rotation was monitored. Forces were applied to the spine by wires powered by an electric motor and were recorded on an on-line pressure transducer linked to a graphic display.

Radio-opaque grids were attached at the moving upper end and fixed lower end of the spinal segment to find the position of the joint when the radiograph was taken. With the use of lead shielding the x-rays were allowed only to penetrate the radio-opaque grids. In this way multiple exposure radiographs were taken and motion of the grids could be followed. Movement from neutral to flexion and neutral to extension was at the rate of 1 degree per minute, until the pressure transducer indicated the limit of elastic stretch. At every 3 degree interval a radiograph was taken while the spine continued to flex or extend, to avoid the phenomenon of creep. Kodak XX film was used to increase resolution. After the spine run was complete a discogram was performed using 2 ccs of Hypaque solution.

Each of the first 25 spines were run by this method. The second group of 22 spines were divided randomly into two groups. All of these latter spines were run four times. In the first group, two runs were performed with no axial loading followed by two runs with 31.8 kilograms of axial force. The spines in the second group were evaluated in a similar way except that loading occurred first. In this way the effects of axial loading on the motion segment of the spine could be determined as well as reproducibility of the centrodes with and without axial loading.

All radiographs were analyzed by means of a Hewlett Packard digitizer and computer. Centres of rotation were performed by the University of Toronto IBM computer with an SAS program. Each radiograph was positioned on the digitizer and a 0 point was set at the posterior superior corner of the L5 vertebral body. Each marker grid and each successive position to which it moved was digitized. These points then characterized the centrode for that spine. The data in the form of X Y co-ordinates was entered into the computer program. Nine independent calculations for each centrode of rotation could be performed and the mean taken as well as the standard deviation, which provided us with accountability of the accuracy. Once the first point of the centrode was determined the computer program continued until all the points of the centrode were identified. These connected points formed the centrode for that spine and the length was then determined by the computer. There was some variation in the size of the specimen tested so a standard length of L5 vertebral body of 4 cm was chosen for the antero-posterior dimension. The co-ordinates' points were multiplied by the appropriate ratio for each specimen to compare the loci.

The average position of each centrode was determined by averaging the points in the locus to give an X and Y position. The length of each locus was determined by the sum of point to point distances in order from full extension to full flexion by the formula:

$L = \Sigma\sqrt{X^2 + Y^2}$ where L = length in mm.

The statistical analysis compared the normal with the other groups with respect to length and position of locus. As well the effect of axial loading was studied. Since there was a large heterogeneity (variability) among the groups, the criteria for parametric testing, that is normality, were not fulfilled. Thus, the nonparametric tests of Kruskal-Wallis and Wilcoxon-Rank-Sum were performed on ranked data.

RESULTS:

Ten of the lumbar motion segments were normal. Ten spines demonstrated minor degenerative disc disease, 11 were mild, 12 were moderate and 4 were severely degenerated. (Table 2). The range of motion is noted in Table 3. Note that in all the degenerative spines, excluding the severe cases, only 25% had an abnormal range of motion (less than 12 degrees and more than 21 degrees). In the minor-mild groups where increased motion would be expected, only 25% had an increased range of motion.

Normal spines traced centrodes in the posterior half of the disc comparable to the single centre of rotation noted by other authors (2). The length was relatively short, less than 30 mm, with an average of 20.9 mm. (Table 4). The direction of the centrode was consistent, passing from posterior to anterior and in some cases posterior again as the spine moved from extension to flexion (Fig. 1). The pattern in the minor category indicated that the centrodes were more complex and had a significantly increased length (average 116 mm) (Fig. 2). In the mild group the length was longer than in the normals (average 78 mm) (Fig. 3). The moderate group tended to be displaced into the inferior vertebral body approximately 10 mm below the other groups on average. Length was similar to the other degenerative categories (Fig. 4). The severely degenerated group had shorter centrodes (average 33.6 mm), that is, the same range as the normal spines. There were too few in this group and too large a variation to determine a trend in position (Fig. 5).

Centrodes were ranked according to length and to their X and Y positions. The Kruskal-Wallis test demonstrated a statistical significance between groups for their length of centrode ($P < 0.005$) and for the Y position only in the moderate group ($P < .01$). The Wilcoxon-Rank-Sum test demonstrated that the degenerative centrodes were longer than the normals ($P < .001$) and the degenerative loci were significantly longer when each individual group was compared to the normals ($P < .01$) except for the severe group ($P > .25$)

The centrodes of the moderately degenerated group were more inferior, located in the body of L5, and this was found to be statistically significant compared to all other groups ($P < .001$).

The effects of axial loading were minimal with the results demonstrating that the 22 axially loaded spines were quite similar to the 47 unweighted spine runs. There were no significant differences in the various degenerative disc disease categories. Axial loading tended to lengthen the centrodes, on average 7.5 mm but this was not statistically significant. Furthermore, there was no significant change in the position (1 mm). Whether the spines were tested initially without weights or with weights made no difference to the length or pattern.

DISCUSSION:

It is assumed that degenerative disc disease results in early instability, that is, increased range of motion (excessive motion) or erratic motion (increased translation). Although excessive motion can be easily documented by flexion/extension radiographs, this form of instability may not appear in the initial phases of degeneration. Furthermore, as degenerative changes proceed, any excess range of motion will fall back to the normal limits as the motion segment stiffens. Hence, flexion/extension films may be negative if done too early or too late. In fact, approximately 25% of the spines noted to be abnormal radiographically had an abnormal range of motion (normal = 14-21 degrees) (12). Even within the subgroups of minor and mild, in which one expects the most motion, only 25% had an abnormal range. Therefore, translational or erratic motion of one vertebra with respect to another may be a more important factor in diagnosing instability. This parameter (translational motion) is more difficult to assess. However, translation relates well to the locating of the centre of rotation in the spinal motion segment. As noted in Fig. 6, translational motion will result in significant changes in the location of the centre of rotation.

By plotting centres and comparing them with normal, one can obtain a more objective evaluation of the abnormal excursion of one vertebral body in relation to another (segmental instability). Comparison of a hinged joint, a normal spine and an abnormal spine motion segment allows one to understand the way in which centrode patterns change with increasing instability. The hinged joint is a totally stable unit allowing no translation for a single pivot point. Thus, flexion and extension will have one point as its centre of rotation without defining a centrode. The range of motion will have no effect as the joint is completely stable without translation. In the normal spine, which is stable, the single centre of rotation for the entire range of motion is in the posterior one-third of the disc (2). The lumbar motion segment is not a perfect hinge joint however, and therefore allows some translational motion. Since the centre of rotation will not be at one point, changes in position form a locus of points or centrode pattern. The abnormal spines with relative instability demonstrate translational motion with possibly an increased range of motion in flexion/extension. Each arc of rotation within the full range of motion will contain a centre of rotation which is different in position from the next arc. Thus, the centrode pattern which forms will demonstrate a centrode pattern which may be longer than normal.

Our data indicates that there is a difference between the normal loci and the different categories of degenerative disc disease. In the minor and mild categories, significant abnormalities occur in the centrode length, which allow detection of instability, in spite of the paucity of radiographic findings. The length of the centrode is significantly greater than normal. These findings suggest that the main abnormality of motion is erratic rather than excessive movement.

The moderately deteriorated discs also demonstrated a shift inferiorly of the centrode into the body of L5. Axial loading had a minimal effect on the centrodes and repeated runs did not appreciably change the length or position.

This technique has demonstrated that 94% of radiographically abnormal spinal motion segments are detected by the centrode pattern method, as opposed to 25% using flexion/extension radiographs.

CONCLUSIONS:

The instantaneous centres of rotation for small angles (3 degrees) is accurate (within 1.0 mm), reproducible and rapid using this method. In normals, the pattern is located within the posterior third of the intervertebral disc and measures approximately 20 mm. Degenerative changes cause an increase in the length of the centrode independent of the range of motion. As degeneration continues to a moderate degree, the position of the centrode shifts inferiorly to the L5 vertebra.

The technique is sensitive, detecting 94% of the abnormal spines, compared with only 25% detected by flexion/extension radiographs. Axial loading had no significant effect on the length or position.

ADDENDUM: CENTRODE PATTERNS IN NORMAL SUBJECTS:

The assessment of centrode patterns in vivo in normal volunteers has recently been undertaken for both the L4-5 and L5-S1 levels (13). Twenty-one normal males, under the age of 32, were assessed for a total of 12 studies at L4-5 and L5-S1.

Because of technical factors it was not possible to employ the exact technique utilized for the cadaver studies. The method was modified to obtaining 5 lateral radiographs of the patient from full extension to full flexion and calculating the instantaneous centres of rotation for each arc of rotation of approximately 3 degrees. Acetate tracings and contour matching techniques recorded the relative positions of the vertebral bodies on each film. Multiple tracings of each radiograph combined with a digitizer and computer were used to improve precision in the calculated centrode patterns.

Centrode lengths were found to measure 43.7 mm and 59.9 mm respectively for the L4-5 and L5-S1 levels.

The study demonstrated precise centrode pattern analysis for sagittal plane motion of the lumbar spine in vivo. Inter-observer and same observer differences were minimal. Studies are now underway to determine whether this technique will be useful as a clinical test in diagnosing early segmental instability of the lumbar spine in patients with low back pain.

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TABLE 1 - RATING SYSTEM

Osteophytes	0 - Normal
	1 - Small
	2 - Large
Range of motion	0 - 14°-21°
	1 - >21°
	2 - <14°
Disc/height ratio	0 - >34
	1 - 25-34
	2 - 17-25
	3 - <17
Discogram	0 - Normal
	1 - Grades I & II
	2 - Grade III
	3 - Grade IV

TABLE 2 - SPECIMENS

Normal	10
Minor	10
Mild	11
Moderate	12
Severe	4
Total	47

TABLE 3 - COMPARING ACCURACY OF RANGE OF MOTION VS CENTRODE - FOR DETECTING ABNORMAL SPINAL MOTION SEGMENTS

(courtesy SPINE)

	ROM			CENTRODE		
	N	Abnormal	% Abnormal	N	Abnormal	% Abnormal
Minor Mild	16	5	25*	1	20	95*
Minor Mild Moderate	25	8	25	2	31	94

* $P < 0.01$

TABLE 4 - CENTRODE LENGTH AND POSITION (courtesy SPINE)

	Length in mm (avg.)	Position in mm	
		X (avg.)	Y (avg.)
Normal	20.9*	11.6	0.6
Minor	115.7	9.1	1.4
Mild	78.0	8.6	-0.6
Moderate	48.7	10.0	-7.8*
Severe	33.6	10.6	2.3

*The average length of the normal centrodes was statistically significant compared with all groups ($P < 0.001$) except for the severe group ($P > 0.25$). The average vertical position (Y-co-ordinate) of the moderate centrodes was statistically different from all other groups ($P < 0.001$).

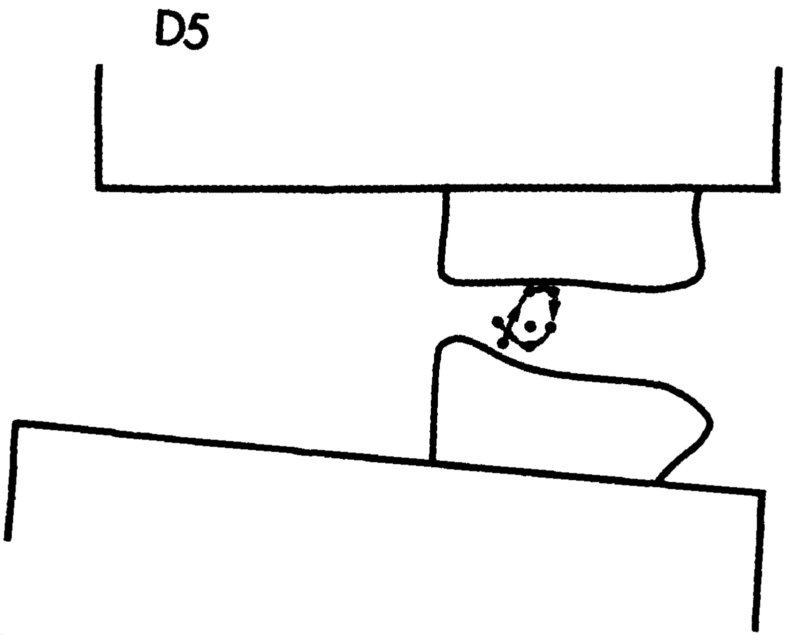

Figure 1 - Normal Spine with Centrode Pattern (courtesy SPINE)

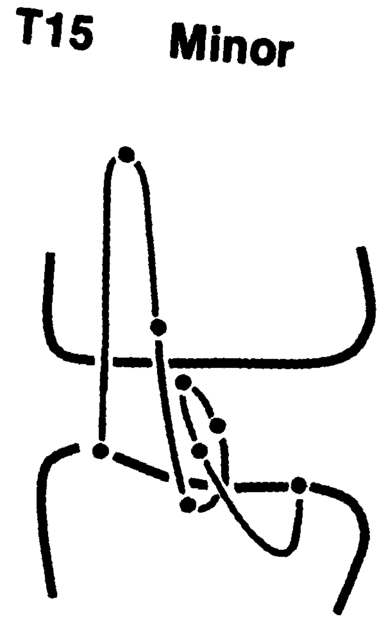

Figure 2 - Minor Degenerative Disc Disease with Centrode Pattern (courtesy SPINE)

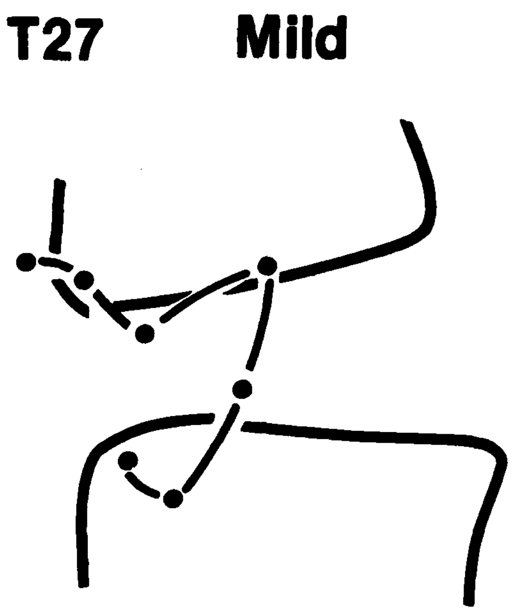

Figure 3 - Mild Degenerative Disc Disease with Centrode Pattern (courtesy SPINE)

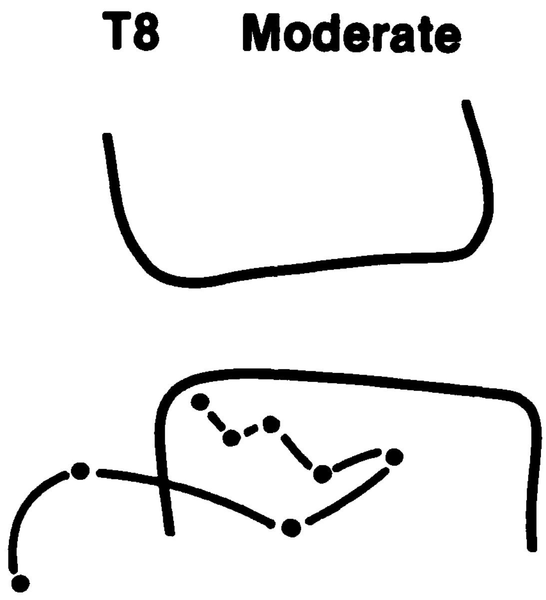

Figure 4 - Moderate Degenerative Disc Disease with Centrode Pattern (courtesy SPINE)

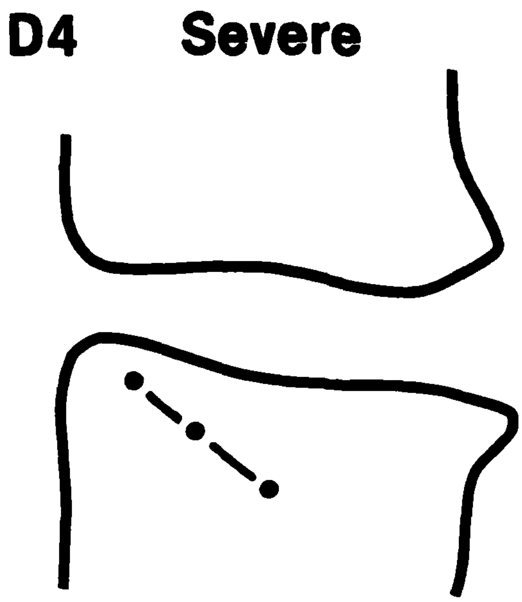

Figure 5 - Severe Degenerative Disc Disease with Centrode Pattern (courtesy SPINE)

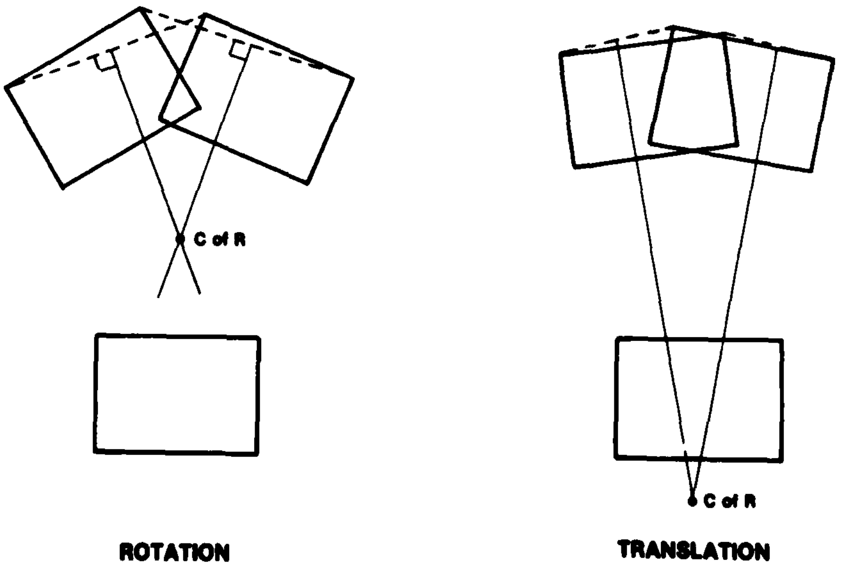

Figure 6 - Movement of the centre of rotation is shown when rotation and translation occurs at the motion segment. Note the large excursion inferiorly of the centre of rotation when translation occurs with rotation. (courtesy SPINE)

DISCUSSION

BOWDEN, CA: Have you considered the centrode length in relation to back pain, since you show that it increases for moderate or mild degeneration and then it decreases in severe cases? We know that back pain is most common among those of middle age and tends to decrease in prevalence among older people, although degeneration itself does increase. Were the more severely degenerated spines from older cadavers, and would you be prepared to comment on the relationship between the centrode length and back pain?

GERTZBEIN, CA: We only had 4 specimens in our severe group, so it is hard to predict what the real lengths would have been in that group. The fact that we are dealing with is that back pain is more of a symptom than a disease. The causes of back pain are legion, so I'm sure there are many factors which will influence the centrode pattern. One of the most important, I think, will be muscle spasm; and I think this test probably will not be very accurate for people with acute back pain because a spasm will limit the motion and, therefore, increase the error of the technique. What I was interested in, when I first got started on this study, was to determine if I could pick out people who had chronic back problems with very little radiographic findings, in order to determine if they were malingerers at functional overlay, or whether there was a real abnormality in the spine that we were not picking up by the usual methods.

AKKERVEEKEN, NE: I have a question about the problem of abnormal movement in a population with so-called symptomatic degeneration versus a population with asymptomatic degeneration. Could you comment on that, and do you expect differences in the motion segment, as far as movement is concerned?

GERTZBEIN, CA: I have tried to emphasize that this is just a test, and it has to be taken into context with other factors. Obviously, the clinical assessment is probably the single most important aspect. If the patient has back pain and other findings on physical examination, but minimal radiographic changes, then this test may be helpful in identifying where the pain is coming from; but I'm sure that there are a number of people walking around who have instability of their spine and don't have pain. I can't explain as to why one person would have pain and another wouldn't.

AKKERVEEKEN, NE: I don't intend to ask you that. You took a population of normals, but I want you to take the next step: to take a population with mild degenerative changes, but without any history of back pain whatsoever; and do the test again, comparing that population with a population of patients with the same radiographical changes in the lumbar spine. That's what I'm interested in.

GERTZBEIN, CA: Well, we're going back even one step further than that now. We're going to take normals in different age groups: under 35, 35 to 50, and 50 to 75 and get the normal values for that group of people. That's the first step.

AKKERVEEKEN, NE: Do they have to have normal X-rays?

GERTZBEIN, CA: Yes; then, from there, we will have to look at those people whose X-rays we find, incidentally, to have asymptomatic degenerative changes, and see what their central patterns look like compared to the normals of that age group. So, it's an ongoing study, and this is one of the questions that we would like to answer.

LANDOLT, CA: How does total body radiation exposure in your technique compare with that used in the standard method for measuring spinal segment motion through flexion/extension radiography?

GERTZBEIN, CA: When we did the studies on the volunteers, we used a technique which gave them about 50% of the radiation exposure of a full set of lumbar X-rays. That full set includes flexion/extension films: AP, lateral, and obliques. So, if we are worried about instability in a patient, rather than expose them to that full series, we can get the same information with our technique at half the radiation. The technique has some flaws in it, and we are now modifying it even more and getting better quality films, but that has increased the radiation exposure from 50% to 66% of the normal study. We are still well below the normal for our hospital, and our hospital gives about 50% of what the community hospitals give in radiography for the spine. So, I think it's a safe technique.

EVALUATION AND PREDICTION OF BACK PAIN DURING MILITARY FIELD SERVICE

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ABSTRACT

Questions regarding back pain in different body positions and earlier sicklisting due to back disorders have been answered by 5 093 men aged 23-47 (average age 37) who were about to do military field service. Fifty-three per cent reported that they had had back pain at some time and 14 per cent stated that they had been sick-listed for more than one month in all due to back trouble. A subsample was subjected to a standardized physical examination of the back, average examination time 9 min, and the frequency and location of pain, stiffness or other impairments are given. Subjects who experienced back pain during field service and whose military post was physically heavier than their civilian occupation had on an average lower isometric strength in abdominal muscles as well as in back muscles than other subjects. The physical examination of the lumbar spine was more efficient in separating subjects who experienced back pain during military field service, than information on earlier sick-listing due to back trouble and heaviness of the military post as compared to civilian occupation.

Disorders and impaired functioning of the back accounts for a considerable number of sick leave days and thereby loss of production in Sweden (4, 5, 6) thus constituting a serious problem. These conditions are often combined with and influenced by psychic, psychological and social factors (5). It is therefore difficult to determine to what extent impaired back function is the main reason for sick-listing ascribed to back disorders.

The back is exposed to a considerable amount of mechanical stress (11). A standardized physical examination of the back mainly concentrated on mechanical function and tenderness in the different parts of the spine has therefore been performed in order to assess the validity for prediction of work tolerance during military field service. The predictive value of self-reported back pain history was also studied.

Sweden has universal conscription for men and basic military training for 9 to 15 months, at the approximate age of 20, which is as a rule followed by three 2-4 weeks refresher courses, to which men up to the age of 47 can be draughted. This study was one part of an investigation regarding health examination before military refresher training. The investigation was ordered by the Swedish government and was carried out by the Enrollment Board of the Armed Forces in co-operation with the Medical Board of the Armed Forces.

SUBJECTS

The subjects were compiled from three studies carried out in different parts of Sweden: Southern Sweden (S), Western Sweden (W), and Bergslagen (B), (i.e. three of Sweden's six recruiting areas). (In the following the areas/studies are referred to as area/study S, W and B respectively). All three areas include urban and rural districts but area B includes more woodland than area S and W.

A representative sample (n=6649) consisting of all men in the areas born on the fifteenth of any month who were about to do their military field service refresher course received questionnaires. Although Sweden has universal conscription for men the sample is biased as men rejected at conscription or during basic training are excluded. Replies were obtained from 5 093 men (i.e. 76.6%) aged 23-47 years, with a mean age of 37 years. The occurrence of back pain was studied in this group. Sub-samples were then selected for further investigations. As the studies were not exclusively concerned with back pain and as the objectives varied somewhat between study S, W and B the criteria for selection varied as shown by Table I. One additional criterion was that participation in the examinations was voluntary.

Almost all subjects in the sub-samples from areas S and W underwent physical examination of the back, whereas the subjects from area B were examined only if they had given an affirmative answer to the question: Are you, or have you been, suffering from back pain? The number of subjects examined is given in Table I.

A follow-up study of back pain during the field service was only included in studies S and B, and here the numbers were further reduced (see Table I) as some subjects had been allowed to postpone their service. In addition some were declared temporarily or permanently unfit for service, and finally some subjects did not return the follow-up questionnaire.

METHODS

I. Back pain history. Questionnaires including 8 questions on back troubles (Table II) were mailed to potential subjects.

II. Standardized physical examination of the back was carried out by specially trained physiotherapists according to a scheme including the following:

(a) Tests of mobility and tenderness. The tests were considered positive if the mobility was reduced or if the movement induced pain.

Straight leg raising test; SLR (bilateral testing supine body position). The straight leg was elevated up to 90 degrees flexion in the hip joint. If this manoeuvre evoked pain radiating distally to the knee the finding was denoted "genuine". This pain is caused by stretching of the ischiadic nerve. A restricted range of movement (<90 degrees) not accompanied by the aforementioned pain was denoted "not genuine". The mosts common cause of the "not genuine" SLR test is that the hamstring muscles are too short to permit 90 degree flexion of the hip. Palpation of the muscles during the test can confirm this.

Hip joints (supine body position). Restriction of movement was defined as inward rotation of the hip joint <10 degrees, outward rotation <20 degrees or inability to extend the hip to 0 degrees.

Cervical spine. All mobile segments between the occiput and the thoracic spine were tested with the patient sitting (8). The term "mobile segment" is used as a comprehensive term for movable structures between two vertebras (7). If the finding was inconclusive the examination was also carried out in supine body position. Both rotation (to the right and to the left) and ante- and retroflexion were tested.

The lumbar spine was tested using two methods, one implying more specific testing of isolated segments than the other.

1. Specific testing (8) (side-lying position) during extension, flexion and rotation of each mobile segment. If pain was evoked and/or the mobility was restricted the test was repeated with the person lying on the other side.
2. Stoddard's "springing test" (17) (prone body position with the lumbar spine in lordosis produced by a pillow placed under the chest). With her second and third finger placed on each side of the spinal processes the physiotherapist exerted a vertical pressure on the spine. The main issue in this test was to establish if the pressure induced pain, but the test also gave some information about the elasticity and the mobility of the segments tested.

(b) Isometric strength of trunk muscles was tested with the subjects standing upright on a non-slip material with the arms hanging loosely. When testing strength in (attempted) forward flexion a strap connected to a strain gauge transducer was placed around the chest immediately beneath the axille. The subject was then instructed to support the lower part of the back against a padded plate and to bend forward as forcefully as possible, without jerking, for 2-3 seconds. The highest value obtained in 3-4 trials was recorded. When testing strength in (attempted) extension the subject was turned around, thus supporting the pelvis against the plate and the strap was placed around the back. Otherwise the procedure was the same as for forward flexion. The transducer and the supporting plate were attached to a stand (manufactured by Medicinska Apparater, Södertälje, Sweden), and counterbalanced so that they could easily be adjusted according to the height of each subject. The transducer and the recording and calibration unit were manufactured by Bofors AB, Sweden.

III. Follow-up regarding back problems during field service. 1-2 months after the physical examination of the back the subjects served for three weeks in their respective posts within the army. Depending on the actual post this meant different degrees of physical work and load of the back from light to heavy. At the end of the field service the subjects answered the following two questions: Did you experience back trouble during the field service? Was your military post physically heavier than your civilian occupation? The answers to these questions were compared to the results of the physical history of back pain.

RESULTS

I. Back pain history .

The percentages of affirmative answers to each question regarding the back and its function are given in Table II. Fifty-three per cent of the subjects stated that they had had back pain, 28 per cent that they got pain when walking and 14 per cent reported that they had been sick-listed for a total of more than one month due to back trouble.

II. Physical examination of the back.

In the cervical spine most positive findings were located to the cranial (C2) and the caudal parts (C5 and C6) (Table III). In the lumbar spine most positive findings were located to the most caudal parts. In the neck joints a combination of pain and restriction of mobility was more common (8 cases) than pure restriction of mobility (3 cases). In the rest of the spine pure restriction of mobility was dominant. There was a good agreement between the results from the two methods for examination of the lumbar spine (Table III). Of the 148 cases with positive findings at the specific test 131 also had a positive springing test. In most cases only one mobile segment was affected (Table IV) but findings involving 2 or 3 segments also occurred. The SLR-test was positive in 42 of the 113 cases in study B and 15 of these were "genuine", i.e. had pain radiating distally to the knee.

Isometric strength in trunk muscles

Significantly lower strength during trunk extension ($p<0.05$) was observed in subjects who stated that they had been sick-listed for more than one month as compared to the other subjects (Table V). During forward flexion no significant difference was shown between these two groups.

The force measured in trunk flexion and extension was on the average significantly lower in subjects with abnormal findings at the physical examination as compared to subjects with normal findings (Table VI).

Subjects who experienced back pain during the field service and whose military post was heavier than their civilian occupation had on an average lower muscle strength in trunk forward flexion (<0.05) and trunk backward extension ($p<0.001$) than other subjects (Table VII).

III. Occurence of back pain during field service in relation to (a) results of physical examination of the back, (b) earlier sick-listing ascribed to back trouble, and (c) heaviness of military tasks relative to civilian occupation.

As can be seen from Table VIII the specific test of the lumbar spine is the factor that best predicts occurrence of back pain during field service. That examination gave correct prediction in 164 cases out of a total of 197, i.e. in 83% of the cases. In Table IX the percentage of subjects with back pain during the service are given for all combinations of the three factors.

DISCUSSION

I. Frequency of back pain and impaired back function.

The finding that 53% of our subjects stated that they had had back pain is similar to the 55% found in men aged 25-44 with heavy manual work (6) and to the 61% found in male employees (average age 40 years) of a Danish factory (15) whereas the incidence is higher than the 44% found in men aged 25-44 with light manual work (6). Our finding of nearly 14% reporting aggregate sick-leave due to back trouble more than one month is naturally somewhat below that found for aggregate incapacity for more than 3 weeks; about 17 and 28% for men aged 25-44 with light and heavy manual work respectively (6).

II. The clinical examination

The time required for the examination averaged 9 minutes. In cases with abnormal findings or impaired function a considerably longer time was needed for additional examinations (e.g. examination of the cervical spine in lying position and examination of the lumbar spine with the subject lying on either side). It is essential that the time reserved for the examination is sufficient as the accuracy of the results will otherwise deteriorate.

Screening of the hip joint was included as disorders of the hip joint can affect the back and particularly the lumbar spine. Roentgenographs were not taken as the correlation between roentgenological changes and back trouble is generally poor (6), although there are some exceptions.

In our study subjects who had relatively heavy military tasks and experienced back pain during the service had on an average lower trunk muscle strength than other subjects (Table VII). Nachemson & Lind (12) also found lower isometric abdominal and back muscle strength in patients suffering from low back pain than in controls, but concluded that this finding was probably due to pain inhibition or fear of pain and a result of prolonged inactivity, i.e. detraining. They considered muscle weakness to be of minor, if any, importance for the genesis of low back pain. This does, however, not exclude that strong abdominal and back muscles are essential for the ability to tolerate heavy loads on the trunk. In addition, it may well be that subjects with strong trunk muscles on the average exert themselves to heavier loads than subjects with weaker trunk muscles, i.e. that the load/strength ratio is about the same for subjects with high and low strength. This could imply that trunk muscle strength is of importance although not demonstrable in some studies due to their design. Prospective studies in which trunk muscle strength is measured prior to the development of back trouble in subjects with different load/strength ratios are thus desirable.

Chaffin (1) found that the job-related low back pain incidence rate was increased about three times in groups of employees on a given job if their average load/strength ratio was above 1.0 as compared to groups with lower load/strength ratios. As that study like ours included subjects who had experienced low back pain prior to the strength testing it does not indicate whether high load/strength ratio is a primary cause of low back pain or if it is a secondary effect. Furthermore, the period of observation was only about one year and average load/strength ratios were used, whereas individual ratios would have been preferred.

Further indications of the possible significance of muscle strength are given by Kendall & Jenkins (9) and Lidström & Zackrisson (10) who in controlled studies found that isometric exercises gave better results than flexion and extension exercises. Dalen (2) also stated that isometric training of abdominal muscles was an effective treatment of back pain in young soldiers. Weakness of abdominal muscles may limit the ability to increase the intra-abdominal pressure, which otherwise is a mean of assisting the spine in withstanding the forces acting on the trunk (for ref see 3).

The usefulness of strength measurements for prediction of back pain can be questioned as there is a considerable overlapping between the frequency distributions of strength values for subjects with and without pain as indicated by the standard deviations given in Table VII. Strength measurements (trunk backward extension), however, has been used for prediction of maximum loads in lifting (14) and might be desirable when deciding if a subject is fit for a military post or a civilian occupation demanding lifting and carrying of heavy loads. Measurements of trunk muscle strength might be more adequate than measurements of leg and arm muscle strength as it according to some authors "is known that the legs and the arms can carry loads far in excess of those which the forward inclined back can sustain" (14). This assumption is supported by a study (13) in which subjects had to lift a 20 kg box 100 times in as short a time as possible, and where the time required correlated better with isometric strength in forward flexion and backward extension than with isometric strength in elbow flexion and knee extension. An alternative approach to the problem is to establish "safe load levels" (3), i.e. loads that can be handled by the weakest fit soldier without increased liability to report back injuries. Within the armed forces it is, however, often more realistic to take advantage of the capacity of the stronger soldiers than to decrease the weight of all heavy loads so that they can be safely handled by any soldier.

The study has strictly been limited to "diagnosis". Therapeutic advising and treatment were excluded in order not to invalidate the study concerning the predictive value of the "diagnosis". A routine examination system should, however, if possible, be combined with therapeutic advising. The physiotherapists found it unsatisfactory not to be given time or permission to advise the subjects.

III. Follow-up study regarding back function during field service.

All investigated factors, i.e. physical examination, earlier sick-listing and relative heaviness of military post, correlated with occurrence of back problems during the field service (Table VIII). The predictive value of a negative test (PVneg) was about the same for all factors (82-89%), whereas the predictive value of a positive test (PVpos) was highest for the physical examination, especially that of the lumbar spine. The average PV for the lumbar spine, specific test, was significantly higher than the average PV for civilian sick-leave >1 month ($p<0.05$) and relative heaviness of the military job (p<0.001). Also when studying combinations of three resk factors (Table IX) it is evident that positive findings at the physical examination is the main "risk factor". The rather low PVpos for earlier sick-leave indicates that even if the history of a previous bout of low back pain probably is the most helpful tip-off for identifying men who will become low back disability cases (16), reliance on history alone is not always sufficient. We think, in agreement with Rowe (16) that a positive history should trigger a back examination, especially when it can be suspected that the subject may distort his own medical history, intentionally or unintentionally, e.g. to get disability pension or to dodge heavy military posts (or acquire a desired job). Back pain without consistent findings may be a manifestation of a situation problem (16).

It should be emphasized that our subjects were not randomly selected. However, the selectional bias was intentional and thought to be appropriate as the same method of selection - i.e. selection of voluntary high risk cases by means of a questionnaire - was intended in the routine application of the health examination that was recommended on the basis of the investigation.

As the objective of the study was to elucidate the possibility of predicting work tolerance, ideally no subjects should have been discharged or transferred to a less demanding job, irrespective of the result of the physical examination. For medical reasons, however, a few subjects with pronounced functional disturbances had to be disharged or transferred, which most probably means that the predictive value is somewhat underestimated. Considering this and the fact that many subjects who at conscription or during earlier service had complaints about the back already had been allocated to less demanding posts or even been discharged, one should not expect very high predictive values for the factors studied.

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Table I.

Composition of sample and subsamples

	Study			
	S	W	B	Total
No. who returned questionnaire	1 790	2 102	1 201	5 093
Reason for selection				
Back pains[a]	0	67	48	115
Other complaints[b]	94	252	170	516
Controls without other complaints	100	0	0	100
Total no. selected	194	319	218	726
No. who underwent				
Testing of back strength	194	308	212	714
Physical examination of the back	194	308	113[c]	615
No. in follow-up study	139	0	58	197

[a] Affirmative answers to questions 1, 5 and 8 in Table II. In study S no subjects were selected because of back pains. However, 31 subjects selected for other reasons had given an affirmative answer to question 8.

[b] Complaints concerning circulation, mental status, digestion, kidneys or joints (other than those connected with back problems).

[c] Only those with an affirmative answer to question 1 in Table II underwent physical examination of the back in study B.

Table II.

Answers to questions about back pain and back disorders

	Study			
	S	W	B	
Number of questionnaires answered	1 790	2 102	1 201	Total 5 093
Questions	Per cent affirmative answers			
1. Are you or have you been suffering from pain in the back?	52.7	51.5	54.4	52.6
2. Is the pain located in the back only?	29.6	20.1	24.2	24.4
3. Is the pain located both in the legs and in the back?	18.0	30.0	29.6	25.7
4. Do you get pain when sitting?	22.1	23.7	26.1	23.7
5. Do you get pain when lying down?	18.5	20.3	20.6	19.8
6. Do you get pain when standing?	27.4	30.3	36.3	30.7
7. Do you get pain when walking?	23.5	28.3	32.5	27.6
8. Have you been sick-listed for more than 1 month in all due to back pain or back disorders?	13.4	13.4	15.2	13.8

Table III.

Frequency and location of positive findings (pain and/or restricted mobility) at the physical examination of the cervical and the lumbar spine in 308 men (mean age 39) from study W

(The location is denoted by the cranially positioned vertebra. The number of subjects with restricted mobility only is given within parentheses).

Cervical spine

	C0+C1	C2	C3	C4	C5	C6	C7
No. of findings	11(3)	19(13)	4(2)	12(8)	21(17)	22(16)	5(5)

Lumbar spine

No. of findings at	L1	L2	L3	L4	L5
a) Specific test	1(0)	1(0)	6(5)	53(40)	100(69)
b) Springing test	1(1)	1(1)	5(4)	48(29)	104(53)

Table IV.

Spread of the positive findings in 308 men from study W
Number of cases with 1, 2 and 3 affected segments

	No. of affected mobile segments		
Findings in	1	2	3
Cervical spine	52	15	4
Lumbar spine			
a) Specific test	135	13	0
b) Springing test	127	16	0

Table V.

Strength of trunk muscles (Newton, N) in subjects from study S in relation to statements on earlier sicklisting

	Earlier sick-listing				
	<1 mo. (n=163)		>1 mo. (n=31)		Significance of difference between means
	Mean	S.D.	Mean	S.D.	
Forward flexion	717	216	680	206	$p>0.15$
Backward extension	895	259	790	271	$p<0.05$

Table VI.

Strength of trunk muscles (N) in subjects from study S in relation to findings at the physical examination of the back

	Earlier sick-listing				
	Normal findings (n=121)		Abnormal findings (n=73)		Significance of difference between means
	Mean	S.D.	Mean	S.D.	
Forward flexion	738	208	664	218	$p<0.01$
Backward flexion	919	247	808	276	$p<0.01$

Table VII.

Strength of trunk muscles (N) of subjects in study S in relation to occurrence of back pain during field service and relative heaviness of military post as compared to civilian occupation (- = military post equal or lighter than civilian occupation, + = military post heavier than civilian occupation,) (n=139)

	No back pain		Back pain	
Relative heaviness	-	+	-	+
Number of subjects	68	50	8	13
Forward flexion				
Mean	769	737	692	582
S.D.	220	190	186	198
Backward extension				
Mean	933	923	941	674
S.D.	255	232	223	207

Table VIII.

Occurrence of back pain during field service in relation to findings at physical examination, earlier sick-listing due to back disorders, and relative heaviness of military post

+ = positive test, - = negative test. PV = predictive value.
PVpos = percentage with positive test who got back pain during field service
PVneg = percentage with negative test who did not get back pain during field service
Average PV is the weighted mean of PVpos and PVneg

Test	Result	Pain	No pain	PVpos	PVneg	Average PV	χ^2	p
SLR	+[a]	12	9	57		80	15.67	<0.001
	-	30	146		83			
Hip joints	+	10	13	43		77	6.20	<0.02
	-	32	142		82			
Cervical spine	+	12	16	43		77	7.59	<0.01
	-	30	139		82			
Lumbar spine	+	25	16	61		83	45.60	<0.001
Specific test	-	17	139		89			
Springing test	+	23	24	49		78	29.94	<0.001
	-	19	131		87			
Earlier sick-listing due	+[b]	17	26	40		74	9.53	<0.01
to back pain	-	25	129		84			
Military post in comparison	+[c]	26	61	30		61	5.93	<0.02
with civilian occupation	-	16	94		85			

a) All positive findings ("genuine" as well as "not genuine")
b) More than one month
c) Heavier

Table IX.

Occurence of back pain during field service in 197 men from study S and B in relation to combinations of three risk factors

Comb. no.	Sick-leave > 1 month	Physical exam of lumbar spine	Relation to military job	Back troubles during field service: Fraction	Back troubles during field service: Percentage
1	+	+	+	7/8	88
2	+	+	-	5/6	83
3	-	+	+	9/14	64
4	-	+	-	4/13	31
5	+	-	+	2/11	18
6	+	-	-	3/18	17
7	-	-	+	8/54	15
8	-	-	-	4/73	5

a+ = military job heavier than civilian ocupation

INDIVIDUAL PREDICTABILITY OF BACK TROUBLE IN 18-YEAR-OLD MEN
A prospective study during military service

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SUMMARY

At enlistment 6.824 young men (mean age 18 years) answered a questionnaire concerning back trouble (BT). Out of these 999 passed a standardized physical examination. A follow-up one to four years later during the military service was done, including the same physical examination and questionnaire. The aim was to study the possibility for predicting BT during this time course and the correlations between the variables at enlistment and at discharge. Several significant correlations were found. From the first physical examination, the pain tests (springing test, coin test) correlated with the degree of back trouble at discharge. The questions concerning 1) Absence from school or work and 2) Effect of BT on every day life before enlistment correlated with the degree of BT at discharge. The highest predictive value, 39%, was shown from the answer to the second question. The answer to the first question showed a predictive value of 25%. None of the examination variables showed predictive value over 20%. Smoking more than 20 cigarettes/day showed a predictive value of 23%. Physical data like height, weight and muscle strength had a predictive value of less than 20%.

AIMS

This investigation was performed to study the frequency and course of back trouble (BT) during military service, from enlistment and during the entire basic training. Special emphasis was given to the possibility of using anamnesis and physical status at enlistment for prediction of BT during the coming military service.

As BT shows a very diverse picture it is difficult to analyze. Furthermore, the individual might not be able to distinguish symptoms from the hip joints, the iliosacral joints and the spine. Therefore very strong correlations between the variables studied can not be expected.

METHOD

During a five month period, all the men who enlisted for military service in the Stockholm area filled out questionnaires concerning back trouble (4). Based on these forms 999 men were selected for an additional physical examination. The physiotherapist's (PT) examination (2, 7) (in order as below) included checking while:

- Standing: 1) Difference in leg length, 2) Scoliosis or deviation from the midline, 3) Measuring the distance from C7 to the horizontal line connecting the two posterior iliac spines.
- Sitting: Maximal passive rotation of the head with slight manual lateral load while noting pain or painful tightness (CERVSUM).
- Prone: 1) Coin test (COINSUM) - light pressure (around 300 gr) with a coin between the spinal processes. 2) Rotation of the iliosacral joint during manual fixation of the sacrum (SISUM). 3) Springing test from L5 to middorsal (SPTSUM).
- Supine: 1) Straight leg raising (SLRSUM). 2) Passive rotations of the hip joint in 90 degree flexion (HIPSUM). 3) Passive extension of the knee joint and dorsiflexion of the ankle.
- Lying down (sideways): Test of passive flexion, extension and dorsal gliding between the lumbar vertebrae (LUMBMOV).
- Standing: Measuring maximal isometric strength (Newton) in flexion (FLEX) and extension (EXT) of the trunk with a strain gauge dynamometer (6).

On several occasions the conscript was asked: "Does this hurt?" If the answer was "yes" it was considered as "pain", which obviously includes even very slight pain. In this report the tests have been treated both separately (e.g. coin test L4-L5, L2-L3, Th12-L1+above Th12) and combined (e.g. coin test: L5+L4+L3+L2+L1+Th12+above Th12 = COINSUM). A number of SUM-variables have been created where 0 means no remark and 1 means one or several remarks. The PT's examination was repeated twice; at the beginning and at the end of the military service. The same PT did all the examinations, and every examination was completely independent from the others. From the routine medical examination at enlistment we also collected the figures for height, weight, maximal physical work capacity (WMAX), (8), and the doctor's evaluation of the back (BACKEVAL) and the legs (LEGEVAL). We have as well the results of intelligence tests (IQ) and the psychologist's suitability test for military service (PSYCHTEST). Military assistants handled the strength tests after being instructed of the procedure. The PT had no knowledge of the results of the routine examination. Until the final examination no information was given to the conscripts concerning training or special back treatment. However, we could not forbid a change of training habits or treatment done on their own or on the doctor's initiative. In addition to the repeated inquiries to the conscripts, we also sent inquiries to their officers in command (OESUM), asking their opinions on the enlisted mens' performances with regard to back function. Some of these answers had to be completed from the doctor's reports. The conscripts were also asked to assess the strain of their military service and how strainful it had been as compared to their normal occupation. The military tasks are all pre-set according to the demands on strength and different health variables. The demands are graded on a scale from 3 to 8, where 8 represents the greatest demand. Corresponding numbers are used during the routine medical examination, where 8 and 9 means perfectly fit. The conscript might be placed in a duty with lower, but not with higher demand than his grade. For every enlisted man in the study we have therefore been able to consider both the duty, its minimal demands, and the enlisted mens' medical diagnoses, according to the coding system. This grading obviously is a rather rough one. Different tasks with the same minimal demand can differ very much.

A previous report on the first part of the study, has been published (4).

Statistical methods

Contingency coefficient, c, has been used as a measure of the strength of correlation. (Neither the usual correlation coefficient, r, or Spearman's rank correlation can be used if one of the variables is expressed in a nominal scale, for example back trouble: Yes, no; or mobility: normal, increased, decreased). Like the usual correlation coefficients the value of c is zero when there is no correlation. But c never reaches the value 1.0 even if the correlation is perfect.The upper limit for c depends on the number of categories for the studied variables. For 2x2 and 3x3 tables the upper limit value is 0.707 and 0.816.

Chi^2 test has been used to judge if the correlations are statistically significant or not. The level of significance is shown as p (probability), i.e. the probability for a random sample to show at least the observed value, even if there is no correlation. It might be pointed out that a correlation may well be statistically significant without being of any practical use for selection or prediction.

Analysis of the drop-outs

The drop-outs are analyzed as follows (Table I): The 120+70 of the 999 who were exempted from military service already at enlisting or between enlisting and drafting are according to the aims of the study no real dropouts. The 72 who have not yet been drafted are to be considered as drop-outs only if they commence their military service. For some of the 45+25 who did not complete their basic training and from some of the 19 in training, answers to the inquiries have been given by their officers in command and/or the enlisted men themselves. Considered as real dropouts are the 144 enlisted men who did not attend the final examination. Also there are 46 questionnaires not answered that were expected from the officers.

In addition there are partial drop-outs due to some unanswered questions.

Key-variables

No individual statement from either a conscript or his officer in command is indisputably the best key in judging how he has met the demands of military duty concerning back function. We have therefore made up a set of so called key-variables.

A. Answers by the conscripts.

Tables II - IV.

The question whether they had experienced any BT is apparently too unspecific to be useful. The 68% who had some BT includes everything from slight pain once or twice to severe pain several times or constantly. The question about 'sick leave because of BT' differentiates better, but 'sick-listing' includes everything from merely not having to carry heavy objects to being absent. Due to all these factors the answer to the question 'The effect of BT on everyday life during basic training?' seems the most adequate key.

B. Answers from the officers.

The answers to the question of how the officers considered the conscript to have performed his duty regarding BT was combined with the answers regarding transfer to a less strainful position. (Table V).

In Table V 20 conscripts could be added to the other 671. These men had their duties changed for other reasons than BT and consequently it is uncertain how they would have been able to perform their original duty regarding back function. The combined figures under 'Total' have been used as the officers' evaluation (OESUM).

The answers to the different key questions are of course correlated ($p<0.001$) but the agreement is not complete. (Table VI).

Three groups were created from Table VII:
1. Agreement between the conscript and his officer that the duty was performed without BT.
2. Other - either not agreement or agreement that there had been some, but not serious BT.
3. Agreement that there had been considerable BT.

(Table VIII).

RESULTS

For frequencies of pain, absence and effect of everyday life at discharge, see Tables IX, X and XI.

The correlation between some results from the examination at enlistment (anamnesis, physical examination and ordinary routine examination) and the three main key variables are shown in Table XII. In the following only the key variable called KEYSUM is commented upon. Even if the correlations are statistically significant they are very weak. The highest predictive value, 39% (Table XIII), was obtained for the question how much BT effected everyday life before enlistment. The second highest predictive value, 25%, was obtained through the question about absence from school or work due to BT. The answer to the question in which position the BT was worst differentiates somewhat as those who had checked off several positions (PAINPOS) had more trouble during the military service, predictive value 20%. From the physical examination only the pain tests (springing test, coin test and test of cervical spine) correlated significantly with the outcome (Table XII). However, the predictive values for these variables were less than 20% (Table XIII). The highest predictive value, 35%, from the routine examination, was obtained for low back function (doctor's evaluation, graded 3-5). For all other data from the routine examination at enlistment the predictive values were less than 20%. Both being tall or short had some predictive value, 16 and 17% respectively as compared to 10% for the intermediate group. Heavy weight and high weight quotient (WEIGHTQ, actual weight/weight predicted from height) both had lower predictive value than normal or low weight. The psychological tests had low predictive value for BT. Smoking more than 20 cigarettes a day (SMOKES) showed some predictive value, 23%. Neither maximal isometric strength of handgrip or flexion/ extension of the trunk, nor the strength demands of the military duty (MUSCDEM) had significant predictive value. A possible explanation for the weak correlation between sick-history, back status at enlistment and BT during military service could be that the conscripts had been exposed to very varied duties. However, neither did the demands of the duty concerning back function or muscle strength (Table XIV), nor did work capacity correlate with the key variables (Table XII).

The conscripts' own opinions of how heavy the military service had been, either absolute (OCCUP 3) (sedentary, light, medium heavy, heavy), or relative to their civilian occupation (REL-LOAD) (easier, similar, heavier) correlated significantly with the key variables (Table XIV).

For this reason the correlations have also been calculated only for those who considered their duty medium heavy or heavy. In this subgroup, however, the correlations between data from the enlistment and the key variables were as a rule weaker than in the total material. The co-variation between the different statements concerning the demands of the duty and the stress this induces is shown in Table XV. Here is also shown the strong correlation between the estimated demands of the duty and the conscripts' own opinions. The estimated demands (BACKDEM, LEGDEM, MUSCLEDEM, WORKDEM) have a strong intercorrelation. An attempt to combine the different variables with discriminant analysis for higher prediction did not give a better result. The number of correctly classified subjects was only slightly higher with several variables in comparison to using only the best predictor. Furthermore the result turned out to be contradictory because certain predictors could separate the extremes from the middle group but could not discriminate between the two extreme groups.

DISCUSSION - GENERAL COMMENTS

The aim of this study was to evaluate the possibilities to predict the occurence of BT during military service starting from anamnesis and physical examination at enlistment and also how much the risk of getting BT depends on the physical demands on the conscript. A problem is that the opinion differs between the conscripts and the officers concerning which of the men got considerable BT during military service. We therefore chose to work with both statements. We made a combination of the opinions of both the conscripts and the officers and got a group of 69 conscripts where considerable BT was noted. The fact that we do not have a definite key is of course a weakness that diminishes the correlation between data from enlistment with the key. Another difficulty is the fact that the conscripts have had quite different work loads, which we took into consideration by using the graded demands of the different positions. However, it is not possible to eliminate the effect of the differences. The physical and social environment during the military service also has been very varying. The time period from enlistment to drafting varies from less than one to more than three years. Because of the doctor's judgement several conscripts have been assigned to duties with low demands for backfunction and -strength, or even been exempted from duty. This routine procedure consequently, at least partly, invalidates the predictability of BT in this study. Taking this into consideration it is not surprising to find difficulties in identifying those who will experience BT without wrongly classifying those who might have been able to fulfil their military duty. The key variables including the answers from the conscripts at discharge show that as a rule the same persons who experience BT at enlistment will also do so when discharged. The effect of BT on every day life was indicated the same at discharge as when enlisting. Several (170) indicated some BT at enlistment but not at discharge. Seventy-one who experienced BT at enlistment stated an increase of the BT at discharge. Of the 31 persons in the control group with no BT at enlistment, 11 had BT during the military service. Being absent from duty or part of it, correlates to being absent before enlistment. However, absence does not correlate to the pain tests at enlistment. This could imply that being absent is part of an acquired behaviour. The military service being assessed as heavier than the civilian occupation correlates to all the key-variables. The majority (402) had sedentary or light work before enlistment. The military duty might of course also be experienced as heavier if the individual has pain.

DISCUSSION

There are few prognostic studies in these age groups. The only one that could stand comparison is Darre et al (3). They have done a study on Danish conscripts with an additional examination of the back and with an extensive inquiry. As key answers they used the decisions made by the board of examiners to transfer conscripts to less strainful positions. The examination and inquiry at enlistment was not repeated during the training. Predictability of causing conscripts to drop out due to BT was low and exceeded 20% only for constant pain, considerably increased distance from fingertips to the floor, and change of work or decreased sports activities due to BT. Darre et al also concluded that the difficulties in predictability partly were due to the fact that the conscripts earlier had not been exposed to heavy work. Nordgren et al (6) found in a study of men during a compulsory military refresher course correlation between anamnesis, physical examination of the back and the outcome of the activities during military service which could be used for prediction in practical routines. However, in this age group (mean age 37 years), BT was more pronounced.

Biering-Sørensen (1) found low endurance and increased mobility (modified Schobers test) to be predictive for first-time-LBT (low-back-trouble) during the follow-up year. But if a consequent guess is made that the person will not experience firsttime-LBT (without taking notice of Schobers test and endurance) the result is more often correct than when using discriminant analysis. This is explained by the fact that the first-time-LBT-group is comparatively small. This is in accordance with the present study where the discriminant analysis did not increase the predictive values for outcome of basic training.

Karvonen et al (5) examined 183 conscripts at enlistment. They reported 9% as being on the sick-list due to BT prior to military service and 9% as having BT limiting their function. These figures correspond to those of our study. They found several statistically significant correlations between special examination and inquiry about BT at enlistment and BT during the military service. However, they do not show how strong (or weak) the correlations are. They do not show any results to justify their conclusion: "Standardized history forms and examination schedules, with the measurement or testing of muscle strength, ought to become a part of the physician's armamentarium, at least in occupational and military medicine, preferably also in the general practice."

CONCLUSION

There are several significant correlations between on one hand inquiry and examination at enlistment and on the other hand BT during military service. It is, however, implausible that the additional physical examination and inquiry used in this study could improve the predictability of BT during military service compared to the routine already existing. The predictive values are not sufficiently high to give individual prognosis with reasonable accuracy.

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Table I.

Drop-outs and missing questionnaires from the officers (OE) and the conscripts (CE)

Time of drop-out	Number	Number of (OE)	Number of (CE)	Number of missing (OE)	Number of missing (CE)
1 = At enlistment	120	-	-	-	-
2 = Between enlisting and drafting	70	-	-	-	-
3 = Not yet drafted	72	-	-	-	-
4 = First two months of basic training	45	14	5	31	40
5 = Later during basic training	25	22	7	3	18
6 = In training	19	7	3	12	16
0 = Completed basic training	648	648	608	0	40
Total	999	691	623	46	114

Table II.

Have you experienced back trouble during the last 6 months of basic training?

	Yes	No	Uncertain	Total
Number	427	193	3	623
Per cent	68.5	31.0	0.5	100

Table III.

Have you during the last 6 months been absent from duty or free from some tasks beause of back trouble?

Absence	Number	Per cent
0 days	442	70.9
1-13 days	142	22.8
2-4 weeks	25	4.0
> 4 weeks	14	2.2
Total:	623	99.9

Table IV.

How much has the back trouble effected your everyday life during basic training?

	Number	Per cent
No effect	369	59.2
Some effect	231	37.1
Considerable effect	23	3.7
Total:	623	100

Table V.

Officers answers about the conscripts' back function

	Transferred due to back trouble	Transferred due to other reason	Not transferred	Total	Per cent
No back trouble		53	358	411	61.3
Some back trouble		7	159	166	24.7
Considerable back trouble	51	1	42	94	14.0
Total	51	61	559	671	100
Per cent	7.6	9.1	83.3	100	

Table VI.

Correlation between different key variables
Contingency coefficient = c

	BT 3	ABSENT 3	EFFECT 3	OE
BT 3		0.38	0.46	0.34
ABSENT 3	0.38		0.40	0.45
EFFECT 3	0.46	0.40		0.43
OE	0.34	0.45	0.43	

Table VII.

Combination of the officers evaluation (OESUM) and the conscripts opinions of the effect on everyday life due to back trouble

EFFECT 3	OESUM			
	MANAGED OK	DID NOT QUITE MANAGE	DID NOT MANAGE	TOTAL
Hardly any effect	276	73	14	363
Some effect	90	82	54	226
Considerable effect	4	4	15	23

Table VIII.

Three groups based on Table VII

	Number	Per cent
No BT 276+73=	349	57.1
Others 14+90+82+4+4=	194	31.8
Agreement about considerable BT	69	11.1
	612	100.0

Table IX.

BT 3	EFFECT 3					
	Hardly any	Per cent	Some	Per cent	Considerable	Per cent
No, uncertain	189	51.2	6	2.6	1	4.3
Yes	180	48.8	225	97.4	22	95.7
Total	369	100.0	231	100.0	23	100.0

Table X.

ABSENT 3	EFFECT 3					
	Hardly any	Per cent	Some	Per cent	Considerable	Per cent
No	317	85.9	118	51.1	7	30.4
1-13 days	48	13.0	85	36.8	9	39.1
At least 2 weeks	4	1.1	28	12.1	7	30.4
Total	369	100.0	231	100.0	23	100.0

Table XI.

BT 3	ABSENT 3					
	No	Per cent	1-13 days	Per cent	At least 2 w	Per cent
No, uncertain	193	43.7	3	2.1	0	0.0
Yes	249	56.3	139	97.9	39	100.0
Total	442	100.0	142	100.0	39	100.0

Table XII.

Correlation between some results from the examination at enlistment and the three main key variables (c = contingency coefficient, p = probability)
1 refers to examination at enlistment, 3 refers to last examination at the end of basic training.

	EFFECT 3		OESUM		KEYSUM	
	c	p<	c	p<	c	p<
BT 1	.13	.01	.07	.20	.11	.02
ABSENT 1	.20	.001	.16.	.01	.19	.01
EFFECT 1	.24	.001	.20	.001	.26	.001
CERVSUM 1	.15	.001	.13	.01	.15	.001
COINSUM 1	.10	.03	.10	.03	.11	.04
SISUM 1	.06	.29	.06	.31	.08	.15
SLRSUM 1	.03	.73	.01	.96	.02	.86
HIPSUM 1	.06	.27	-.07	.18	-.10	.05
LUMBMOVSUM 1	.06	.32	.06	.25	.07	.20
SPTPAINSUM 1	.13	.01	.04	.61	.10	.05
HEIGHT	.11	.13	.13	.02	.13	.03
WEIGHT	.08	.44	.08	.34	.08	.42
HANDGRIP	.07	.55	.10	.14	.12	.06
WMAX	.15	.01	.15	.01	.15	.01
LEGEVAL	.08	.45	.05	.77	.07	.55
BACKEVAL	.20	.001	.13	.02	.21	.001
IQ	.05	.78	.08	.34	.07	.51
PSYCHTEST	.11	.13	.03	.96	.10	.19
EXT/FLEX	.09	.23	.09	.26	.11	.14

Table XIII.

Predictive value (per cent of those who at enlistment stated BT and did not manage the basic training without BT, according to different judgements).
Within brackets, per cent of those who did not state BT at enlistment and yet had BT during basic training

	Pos (%)	EFFECT 3	OESUM	KEYSUM
BT 1	94	3.8 (2.7)	14.4 (7.1)	12.6 (2.7)
PAINPOS	28	5.5 (3.2)	19.7 (12.5)	19.8 (9.9)
ABSENT 1 (>2 weeks)	3	10.0 (3.4)	22.7 (13.9)	25.0 (11.6)
EFFECT 1 (considerable)	5	9.7 (3.4)	39.4 (12.3)	38.7 (10.2)
CERVSUM 1	55	3.8 (3.6)	15.2 (12.6)	13.2 (10.5)
COINSUM 1	31	6.2 (2.6)	11.5 (15.1)	9.9 (12.9)
SISUM 1	20	4.8 (3.4)	17.5 (13.1)	13.8 (11.5)
SLRSUM 1	80	3.4 (4.9)	14.0 (13.8)	12.3 (10.7)
HIPSUM 1	82	3.1 (6.3)	12.9 (19.1)	10.5 (19.1)
SPTPAINSUM	54	4.2 (3.1)	14.6 (13.3)	13.1 (10.6)
MUSCDEM >5	11	5.7 (3.3)	19.2 (13.2)	17.4 (11.1)
WORKDEM >5	20	4.8 (3.2)	17.8 (12.9)	14.3 (11.2)
SMOKES >20	5	10.0 (3.4)	17.1 (13.8)	23.3 (11.4)
HEIGHT				
SHORT (<171 cm)	9	1.7	17.7	17.2
AVERAGE (172-185 cm)	67	4.1	11.1	9.8
TALL (>186-)	24	3.3	19.0	16.0
WEIGHT				
LIGHT (<59 kg)	10	3.1	10.0	10.9
AVERAGE (60-84 kg)	80	4.0	15.0	12.8
HEAVY (>85 kg)	10	1.6	10.0	6.6
HANDGRIP WEAK (<530 N)	14	2.3 (3.3)	10.8 (12.7)	9.2 (10.5)
WMAX LOW (<215 Watt)	19	2.5 (3.8)	20.8 (14.5)	18.5 (12.7)
BACKEVAL 3-5	3	11.8	33.3	35.3
6-7	22	5.8	17.8	18.0
8-9	75	2.8	12.0	9.3
IQ -3	19	5.0 (3.4)	18.3 (13.0)	16.8 (10.4)
PSYCHTEST -3	17	2.8 (3.9)	13.8 (14.0)	15.4 (11.2)
HEIGHTQ HIGH (>0.306)	17	7.5 (2.9)	16.5 (13.5)	15.2 (11.3)
WEIGHTQ HIGH (>1.13)	20	1.6 (4.2)	12.9 (14.3)	7.3 (13.2)
BACK TALL	17	7.8 (2.9)	17.3 (13.3)	17.6 (10.9)
EXT WEAK (lower 1/3)	14	5.5 (3.4)	11.5 (14.4)	12.2 (12.0)
FLEX WEAK (lower 1/3)	17	6.7 (3.1)	12.7 (14.2)	11.5 (12.1)

Table XIV.

Correlation between BT or backfunction during basic training and the different demands during the training

	BT 3		ABSENT 3		EFFECT 3		OESUM		KEYSUM	
	c	p<	c	p<	c	p<	c	p<	c	p<
OCCUP 3	.13	.02	.25	.00	.14	.06	.15	.04	.17	.01
RELLOAD	.21	.00	.25	.00	.23	.00	.23	.00	.25	.00
MUSCDEM	.04	.65	.15	.01	.08	.43	.08	.32	.10	.19
WORKDEM	.08	.15	.17	.01	.07	.46	.09	.27	.08	.38
LEGDEM	.08	.15	.10	.19	.05	.80	.07	.55	.08	.50
BACKDEM	.08	.15	.10	.20	.05	.80	.07	.55	.08	.50

The outcome is best predicted by the question of how much BT before enlistment effected everyday life.

Table XV.

Correlations between estimated demands and the conscripts own judgements

	OCCUP 3		RELLOAD		MUSCDEM		WORKDEM		LEGDEM		BACKDEM	
	c	p<	c	p<	c	p<	c	p<	c	p<	c	p<
OCCUP 3			.40	.001	.49	.001	.48	.001	.46	.001	.46	.001
RELLOAD	.40	.001			.16	.01	.32	.001	.25	.001	.25	.001
MUSCDEM	.49	.001	.16	.01			.52	.001	.55	.001	.55	.001
WORKDEM	.48	.001	.32	.001	.52	.001			.58	.001	.58	.001
LEGDEM	.46	.001	.25	.001	.55	.001	.58	.001			.81	.001
BACKDEM	.46	.001	.25	.001	.55	.001	.58	.001	.81	.001		

DISCUSSION

TROUP, UK: In the army, and certainly with reservists who are coming in for four weeks, or a few weeks anyway, there may be positive advantages in reporting back pain. I'm concerned about the applicability of the selection to what may be useful as a selection technique for other populations. Could you tell us, first of all, whether you have looked at the prevalence of reports of back pain in control populations who have not been put through your tests? Secondly, have you applied your tests to study the predictability of back pain in industry?

NORDGREN, SWEDEN: The frequency of back pain has been stated in many studies, as you know -- up to 80% in some studies. So that differs very much; but it differs, I would say, in how the questionnaire is made -- if it is an interview or a question. So yours is a difficult question to answer. We sent out questionnaires, and then we took a sub-sample and gave 300 persons the same questionnaire. When they turned up for the physical examinations, they had to answer the same questions again. If there was just one statement, then there was a reproducibility of around 85 to 90%; but if there were 2 or 3 statements involved in the question, then there were lower reproducibilities. So, certainly, its a very important point. Was there also another question?

TROUP, UK; I think you covered my other question. It really concerned the epidemiological effects of the methods of examination themselves. In other words, did the method of testing the reservists predispose them to report back pain? When one does studies like this, in any occupation, there tends to be a Hawthorne effect; i.e., the people that you are studying tend to comply with what you are interested in. The question is whether the actual exposure to your testing encouraged the reporting of subsequent back pain. That is why I asked whether you knew the incidence of reports of back pain in control populations not so tested.

NORDGREN, SWEDEN: I see your point. You are asking if there is a perceived advantage to answering in a certain way. The study with the personnel in the refresher courses was made voluntarily. They could go through the tests or they could refuse to do them. In the other test, the one involving the 20-year-olds, they had to answer the questions; and, of course, we cannot exclude the fact that they might have thought that something might happen. However, we were very careful not to interfere with the routine examination during the day they were there for testing. They were tested not only for the back, but also for the circulatory and other systems.

HELLSING, SWEDEN: I can add further to the answer from Dr. Nordgren. The younger ones answered their first questionnaire together with the psychological tests when they started their first day of enlistment examinations. So they didn't know what would come out of it. They had similar questions in the routine questionnaires sent in advance. What happened was that, after this, of 951 who stated some pain initially, when they were taken in for examination of back pain, only one said: "No, I just wrote it because maybe I could be exempted". But that was the only one, compared to 5 of the 45 who stated that they had no pain. I didn't know in advance what they had answered; but afterwards, my assistant told me that this person was from the no-pain group. So I asked: "Are you certain that you have no back pain?", and 5 of those 45 said: "Oh yes, some; of course, everyone has some back pain". It's not valid in the statistical sense, but it does give some hint as to what happened.

A REVIEW OF THE NDMC
BACK CARE EDUCATION PROGRAMME

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SUMMARY The Back Care Education Programme (BCEP) at the NDMC, directed to the prevention of recurrent Low Back Pain (LBP) is described from its development in 1978 to the present. The course content is also described, and the vicissitudes governing the transformation of the BCEP from a 10-hour five day course conducted twice a month, to the 8.5-hour two day course, to the present 7-hour one day course. Patients were surveyed through initial questionnaires and review questionnaires sent to them 6 months after education. Results show that little demonstrable difference was found between the 5-day, 2-day and one-day courses. The BCEP has proven very effective in preventing the LBP condition from worsening; less effective in reducing continuous pain; very effective in controlling further attacks of LBP. The BCEP also resulted in 71.5% patients requiring no further treatment and in reducing activity limitation. The BCEP has enabled its clientele to be more responsible for continuing care of their backs by persuing a regime of regular exercise, activity and behaviour modification and postural control. The BCEP has also proved cost effective in increasing the overall effectiveness of DND personnel in reducing the number of days lost due to back injury. (Key Words: Back Care Education; Military Trade-related injury; DND Incidence of LBP; Value of Back Care Education).

Introduction

The subject of Low Back Pain has received an enormous amount of attention in the last fifteen years, particularly in the fields of biomechanical and clinical research. The resultant greater understanding of this complex condition has led to improved diagnostic skills and advances in treatment and management. Although at least 70% of the Canadian population may expect to be afflicted with Low Back Pain at some time in their lives[6], the problem is self-limiting in its course. Statistics have demonstrated that 44% of patients with a first-time incidence of low back pain were better within one week, 86% were better within one month, and 92% within two months. Only 8% had persistent pain beyond two months[2(b)].

The NDMC surveys, however, are not in accordance with these previous findings. The NDMC patient surveys show that since the first-time incidence of low back pain, low grade ache or pain continues to exist, and out of 271 males surveyed in 1984,

38.4% had pain for up to 6 months' duration;
11.4% had pain for up to 12 months' duration;
11.4% had pain for up to 3 years' duration;
8.2% had pain for up to 5 years' duration; and
30.6% had pain for more than 5 years.

It is noted that the majority of BCEP participants are suffering from recurrent back pain, therefore the statistics can be anticipated to be different from the general statistics quoted earlier. The problem lies in the tendency of low back pain to recur, with each successive recurrence becoming progressively more severe and incapacitating. Approximately 60% of those with first-time episodes of low back pain suffer recurrence.[3] Successful management of low back pain over the long-term must therefore include patient education and the teaching of prophylaxis.[1,3,5,6,7,9] Educational programmes have been reported to not only reduce the frequency of absenteeism from the work place, but have enabled those with chronic, longstanding back pain to retrieve a quality of life previously not thought possible.[9]

Cost to the Economy

The cost of Low Back Pain to the economy can be measured financially only in terms of compensation for work-related injuries. The Workers' Compensation Board of Ontario, for instance, remunerated injured workers a total of $399.3 M in 1984 excluding the cost of lost productivity for back injuries sustained on the job. These back injuries constituted 27% of all reported work-related injuries, and of the entire number of claims submitted for back injury, 49.4% were re-opened claims[21], the term "re-opened" meaning a first-time injury sustained at work again by the same claimant. The term "recurrent" is invalid for compensatory purposes. In comparison, with a much smaller population of approximately 83,000 in strength, the Canadian Armed Forces' (CAF) disabling back injuries sustained at work constitute 20% of all reported work-related injuries.[19] The term "disabling" is defined by the Directorate of General Safety as having cost involved for absence from work for recovery, and not disablement in the medical sense. This cost includes Direct costs, i.e. salaries, and Indirect costs, i.e. medical, administrative and replacement personnel expenses, and is estimated to be approximately $600.00 for one member's absence from work per day. The number of work-related back injuries in the CAF may seem to be a little lower than the provincial average, however, it is suspected that not all of these injuries are reported to the Directorate of General Safety.

Cost to DND for CAF and Civilian Work-Related Back Injuries

Of the Low Back Pain population, determined so far, only the back injuries sustained at work are reported to the Directorate of General Safety. These data are at best only an approximation owing to an as yet imperfect and non-compulsory reporting system.[19] In determining the cost in non-productivity to the Department of National Defence's (DND) economy due to back injuries on the job, the Directorate of General Safety concluded that approximately 500 back injuries in the CAF were reported for Fiscal Year 1984-85. Twenty percent of these (i.e. 100) were classified as Disabling, each requiring 5.13 days' absence from work for recovery. The total cost in lost productivity for the Department at $600 per day was therefore $307,800. The cost associated with the other 400 non-disabled members, based on an estimate of $200 each for medical and administrative costs by Treasury Board, was $80,000. The total expenditure for CAF work related back injuries for FY 1984-85 was therefore approximately $387,800. In contrast with the CAF component of the DND, 500 Disabling back injuries at work were reported by the DND Civilians, who number 37,500 in strength and constitute 30% of the Departmental strength. The DND Civilian with a work-related back injury is awarded an average of 21 days' injury-on-duty leave during which time he continues to receive 100% of his salary, the Worker's Compensatory portion of which is tax-deductible for the time he is incapacitated. Direct and indirect costs in non-productivity for the civilians amounted to $6,500,000 for FY 1984-85. The BCEP is not yet made available to the DND Civilian Members. The total costs of the DND budget for work-related back injuries to the civilian and military personnel approximated almost $7M in Fiscal Year 1984-85. The annual expenditure in the DND budget for Low Back Pain in the military and civilian personnel, for both work-related and non work-related causes approximates $23,600,000 per year, or almost 0.27% of the current total DND Budget.

Cost to DND for CAF Work - and Non-Work - Related LBP

Owing to a manual data entry system at the Base level, and to the unreliability of timely submission of the registers of data on an annual basis, attempting to determine the exact extent of Low Back Pain in the CAF through the manual retrieval of information proved a laborious task. To obtain an estimate of the Low Back Pain cases seen on an Outpatient basis a search through the data representative of 50% of the Bases, Stations and Ships for the year 1983-84 revealed that 23.22% of the CAF population had reported Low Back Pain from work and non-work related injuries. This estimate roughly corresponds to the 27% of back disorders treated in the CAF Physical Therapy Departments.[20]. The cost to the Department in CAF time lost from duty, medical, and administrative expenses approximated $16,735,600 for this period. Of the population with Low Back Pain, based on a five-year survey[22], an average of 0.42% received hospital care of approximately 8.75 days each, costing the Department $1,830,150 per year. The BCEP is at present available only to military personnel on a few Bases where Physical Therapy Services exist, and at the NDMC.

Incidence of Back Injury Related to Trade

While the Directorate of General Safety directs its energies to the prevention of first-time back injury, the BCEP is responsible for the prevention of recurrent back pain in an already afflicted population, and therefore remains essentially in the medical domain. As military medicine is both Occupational and Preventive, liaison with the Directorate of General Safety in the identification of military trades reported to be more conducive to the generation of back problems has permitted more specificity in the educational content of the BCEP for military personnel, and has enabled lecturing staff, primarily the Physical and Occupational Therapists to be more aware of potential occupational hazards in target groups.

A breakdown of the most vulnerable Trades for Trade-related injuries in the CAF is tabled below. The vulnerability of trades to back injuries is ranked according to the relationship between back injuries and all reported injuries, not according to frequency or severity. It will be noted from a comparison of tables 1 and 2 that vulnerability and severity bear little relationship to each other, but can be used to establish the ranking of trades as target areas of concern and preventative education.

Table 1

Trades Most Vulnerable to Back Injury by Military Occupational Category (MOC)

CAF Average of Disabling Back Problems
= 19.8% of all Reported Injuries (1980-1985)

Rank	MOC	Population	Back Disabling Injuries / Total Disabling Injuries	Back Injury * Frequency Rate (Rank)
1	Traffic Techs (Air)	824	37.8%	0.34(1)
2	Weapons Techs (Air)	949	35.2%	0.15(7)
3	Supply Techs	3958	34.1%	0.14(9)
4	Motorized Support Equipment Operators	3076	27.6%	0.19(5)
5	Air Frame Techs	2022	25.9%	0.22(4)
6	Vehicle Techs	2791	25.2%	0.222(3)
7	Metal Techs	477	21.9%	0.29(2)
8	Crewmen (Tanks)	1749	19.0%	0.09(11)
9	Aero Engine Techs	1723	17.1%	0.08(12)
10	Cooks	1708	15.1%	0.16(6)
11	Bosuns	682	13.8%	0.12(10)
12	Field Engineers	1092	12.5%	0.146(8)
13	Infantrymen	6183	11.7%	0.07

*Injury Frequency Rate = # disabling back injuries/100 person-years.

Table 2

Severity of Trade-Related Back Injuries by Military Occupational Category (MOC)

CAF Average Number of Days Lost per Year for
Back Injures = 18.8% of Total Days Lost
for all reported Injuries (1982-85)

Rank	MOC	% Days Lost per Year Within Trade for Back Injuries	Average Back Injury Severity Rate (Rank) *
1	Cooks	55.6%	3.80(1)
2	Air Frame Techs	46.3%	1.12(5)
3	Vehicle Techs	41.7%	1.53(2)
4	Supply Techs	30.9%	0.69(9)
5	Field Engineers	27.4%	1.49(3)
6	Metal Techs	22.9%	1.33(4)
7	Weapons Tech (Air)	19.4%	0.63(10)
8	Motorized Support Equipment Operators	17.9%	0.87(8)
9	Traffic Tech	16.7%	0.32(12)
10	Aero Engine Techs	12.6%	0.33(11)
11	Infantrymen	12.2%	0.95(7)
12	Bosuns	9.5%	0.98(6)
13	Crewmen (Tanks)	7.0%	0.27(13)

* Injury Severity Rate = # Days Lost/100 Person-Years.

The hypothesis inferred from these tables indicates that certain trades need an educational programme tailored to their specific needs, including methods of dealing with particular, frequent, or repetitive occupational activity, positions or postures.

History of the NDMC Back Care Education Programme

Practically all treatment for Low Back Pain conducted in the Physical Therapy Department at the National Defence Medical Centre (NDMC) is directed to the occupational return of the patient, and to the prevention of recurrent back injury. Treatment methods are based on the diagnosis of the referring physician or consultant, and on the assessment of the Physical Therapist. The following affective components are dealt with separately:

1. The mechanical condition itself.
2. the pain.
3. the limitations facing the patient, some of which may be self-imposed.

The third component is considered to be largely responsible for vulnerability to recurrent episodes of incapacitation, and, following appropriate treatment education is most important in its prevention. Educational aspects used to be conducted by the Orthopaedic surgeon and the Physical Therapist during consultation, on a one-to-one basis, an enormously time-consuming task particularly as much of the same information had to be repeated countless times each week. Although education on an individual concept has obvious merit, it is a more expensive endeavour as patients require a total of 3-6 hours' instruction each[7]. At the NDMC, group education has been found to provide the patient with a better comprehension of spinal function, less taking of the part for granted, and has imparted to the patient himself a large part of the responsibility for the care, well-being and restoration of function of his back.

Largely to economize on the time of the professional staff and to continue providing patients with the knowledge they require, the NDMC Back Care Education Programme (BCEP) was developed. It was launched in July 1978 and was directed to complete the treatment of back and neck pain of mechanical origin by teaching patients how to prevent recurrent problems. The programme was then under the direction of the Chief of the Orthopaedic Division, LCol O.T. Portner (now retired), who made it policy that all patients who suffered a back injury were to be educated. The exceptions included those with metastatic tumours of the spine, those with osteoporosis of the spine and those requiring highly individualized programmes, e.g. ankylosing spondylitis. Those with spondylolisis and mild grade spondylolisthesis were also included in the classes but their conditions were made known to the principal lecturer who would caution against certain activities and postures. We took advantage of the experiences of the Canadian Back Education Unit which had commenced its services in 1974[6]. Patients were referred to the Programme by their Physicians and Physical Therapists, and were fully assessed by the Outpatient Physical Therapists prior to education as treatment was occasionally necessary. Patients were also referred from neighbouring Bases. Classes were deliberately kept small with never more than sixteen patients and observers in each. The normal group size was twelve and considerable individual attention could still be afforded patients.

The Five-Day Education Programme

Between July and December 1978, the Programme was conducted twice a month, for two hours a day from Monday to Friday, and enjoyed the full support and participation of the Division of Orthopaedics, Departments of Physical and Occupational Therapy, Department of Psychiatry and the Dietary Department.

This ten-hour Programme included a fairly comprehensive coverage of the following subjects:

- the Anatomy and Pathology involving the Lumbar and Cervical spine, including the course of degeneration of the disc, facet joint dysfunctinon, osteoarthritis, bulging and herniated discs, strains, sprains and postural dysfunction. This lecture was provided by the Chief Orthopedic Surgeon.
- the Mechanical Principles involving function of the spine, including the principles governing movement, load, stress and strain; the principles of postural control; the role of re-achievement of full range of movement in the prevention of recurrent problems. This lecture was provided by a Physical Therapist.
- the Psychological Implications of chronic pain, including factors affecting the perception of pain; inseparability of the physical and emotional components; recognition of factors likely to produce pain and the reduction and management of stressful situations. This lecture was provided by the Chief of the Inpatient Psychiatry Division.
- the Modifications in all Activities of Daily Living, and use of all these modifications to good mechanical advantage to the back in the home, office, and in the vehicle. This lecture was given by an Occupational Therapist.
- the Modifications necessary in specific sports in order to prevent recurrent injury; an analysis of the beneficial and potentially harmful sports. This lecture was provided by the Sports Injuries' Physical Therapist.
- Dietary Counselling. This lecture was provided by a Dietitian.
- An exercise session to include the necessary stretch, mobility and strengthening exercises in encouraging full range of movement and strength of appropriate musculature. This session was conducted by a Physical Therapist.
- A deep relaxation session aimed at the detection and control of muscular tension. This session was conducted by a Physical Therapist.
- Patients' Question Period - all questions were answered. This session was conducted by a Physical Therapist.

Teaching Aids

Teaching aids included slides, slide projector and screen, blackboard, a mobile spine, a pair of lumbar vertebrae for each patient, and a few sets of cervical vertebrae. The patients provided considerable interaction, mainly in information exchange and mutual support. The atmosphere then, as it still is now, was relaxed, one of positive reinforcement, and enthusiastic in approach to the subject of Low Back Pain. The Programme was also considered to be most helpful by the nursing staff who attended, in their care for the patients in hospital.

Questionnaire and Quiz Completion

Patients who attended the BCEP were required to complete a ten-question multiple choice anatomy and pathology quiz prior to education, to determine their basic comprehension of low back pain and its course. The results consistently demonstrated a maximum of 20% correct answers! The post-education quiz results demonstrated an average of 90% comprehension. The patients were also required to complete a basic Questionnaire on the history and nature of their back pain. These questionnaires were classified confidential when completed. A Review Questionnaire was sent out to the patient six months later for follow-up purposes and to determine the value of the educational role in treatment. The original Questionnaires used for these purposes were designed by the Canadian Back Education Unit and had to be sent to Toronto for computerized data processing.

Problems Encountered with the Five-day BCEP

Although most well-established Programmes are conducted over weekly periods ranging from two to four weeks,^{5,6,7,12,14} mainly for continuous positive reinforcement purposes, the initial experience at the NDMC from July-December 1978 was subject to several frustrations:

- patients' attendance dwindled after the first three days' lectures. Those attending from Headquarters could not always get away from scheduled or unscheduled business;
- lecturers on the Medical Team could not always be present owing to emergencies arising;
- lecture room bookings would be cancelled by other departments at short notice for other hospital functions and alternative arrangements would have to be made.
- patients from other Bases could not always attend owing to the expense involved with temporary duty travel for a week.

With regard to subject matter, small concerns arose regarding the need for a dietary counselling session; only the occasional patient required this and would have preferred personal consultation with his dietitian. The value of a single deep-relaxation session was also questioned as most patients required more practice, and the only session experienced during the entire programme was invariably severely interrupted with a great deal of snoring and escalating laughter culminating in convulsions. So much for traditional deep relaxation en masse!

The Two-Day Programme

As a result of all these difficulties experienced in a six-month period, the two-day programme emerged in 1979, and continued thus until October 1984 when it was revised once more. The two-day programme was a great deal more efficient in terms of administration, management and organization within the limited resources of time and personnel. The BCEP continued to be conducted twice a month, on Mondays and Tuesdays, and contained essentially the same itinerary with the exception of the Dietary Counselling and the Deep Relaxation Sessions. This eight-and-one-half hours' programme conducted over two days enjoyed an excellent attendance record for both days, both from the Ottawa Bases, and National Defence Headquarters, and permitted attendance by those from Bases further afield.

Another change took place in the summer of 1983 when the Chief of the Inpatient Psychiatry Division, LCol M. Lange, was posted out of the NDMC and replacement support to the Programme was not available. Prior to his departure, in order not to lose this integral part of the programme, his lecture was recorded on Video Cassette Recording for all future classes. Teaching aids today include a television and recorder. In the two-day programme all patients continued to complete the anatomy and pathology quiz before and after education, as well as the comprehensive questionnaire designed by the Canadian Back Education Unit[6]. All patients continued to be reviewed by questionnaire after six months.

Review Assessment

At review, patients reassess their condition and rate themselves with the following grades:

0 = worse; more pain; increased disability
1 = no change
2 = slight improvement; same amount of pain; some decrease in disability.
3 = fair improvement; slightly decreased pain; moderately decreased disability.
4 = good improvement; moderately decreased pain; largely decreased disability.
5 = excellent improvement; largely decreased pain; no disability.

Although very much a subjective measure, Grades 3, 4 and 5 are considered satisfactory improvement. Grades 0, 1 and 2 are unsatisfactory and the patient is advised to return for reassessment, treatment if necessary, and to attend a refresher course.

Staffing Constraints and Trial of the One Day Programme

In 1981, the Chief of Orthopaedics then, LCol Portner, could not continue to lecture for the BCEP owing to staffing constraints in his Division and this task was delegated to the senior Physical Therapist. The Programme today is conducted entirely by the Department of Physical Medicine and Rehabilitation staff. In 1984, further revision of the Programme took place, consequent upon a professional staff shortage in the Physical Therapy Division, and re-organization involved contemplation of condensing the two-day Programme into one day. Serious consideration was given to the possibility of deterioration of its quality and the retention of information by patients who would no longer have the opportunity for clarification or expansion of an issue thought about overnight. In addition, time constraints would force an atmosphere charged with increased intensity and would be therefore less relaxed. In spite of these fears, a three-month trial of the One-Day Programme was conducted to establish its feasability.

One Day BCEP Changes and Problems Encountered

Only absolutely essential subject content was retained; the pre- and post-education quizzes were eliminated, and the Initial Questionnaire was completed prior to attendance, and brought to the classroom for submission. In the past, the completion of quizzes and Initial Questionnaires would absorb at least one half hour of classroom time. The Initial Questionnaire, however, was necessary in order to provide reference for review by Questionnaire six months later.

The trial proved that a one-day Programme was perfectly acceptable to both the patients and staff after a few initial concerns were settled. These concerns involved coffee breaks, and question periods. When the two-day Programme was being conducted the classes started at 1000 hours so a morning coffee-break was quite unnecessary. An afternoon coffee-break was not necessary as patients generally arrived in the gymnasium for the exercise session at this time. Lunch was provided at hospital expense. As the patients were now starting at 0800 hrs a break had to be provided between 0800 and 1200 hrs. Fifteen minutes did not provide sufficient time for patients (some of whom had difficulty moving swiftly), to go to the Cafeteria, queue up, have coffee and refreshments, and return within that time. Time constraints did not permit a half-hour break which would have been ideal. After considerable administrative agonizing this dilemma was solved with the provision of coffee in the classroom. This has had the added beneficial effect of providing a more informal atmosphere. The two-hour question period provided in the two-day session which permitted individual problems to be dealt with in their entirety, had to be dispensed with in the one-day session. Question period then became dispersed in short intervals after lecture series and occasionally over lunch.

The One-Day BCEP Content

The present one-day Programme is still conducted two or three times a month, depending on demand, and is held on Mondays. The itinerary for the day is as follows:

0800-0830	Welcome and Registration; collection of completed Initial Questionnaires
0830-0930	Anatomy and Pathology Lecture
0930-0945	Coffee break and Questions
0945-1045	Mechanical Principles in Spinal Function and the Prevention of Recurrence (Lecture).
1045-1100	Question Period
1100-1200	Modifications in the continued practice of Sports and Recreational Activity (Lecture)
1200-1245	Lunch
1245-1315	Question Period
1315-1400	Psychological Implications of Chronic Pain (Videotaped Recording)
1400-1445	Modifications in the Activities of Daily Living (Lecture but soon to be a practical session in the Occupational Therapy Division)
1445-1500	Question Period
1500-1600	Exercise Session in the Physical Therapy Division gymnasium
1600-1615	Closing Remarks

Cost Effectiveness and Quality: One-Day BCEP

That the one-day Programme is more cost-effective in comparison with the former two-day Programme is undoubted. The teaching intensity has increased and no perceivable deterioration in quality has occurred, due largely to the long-term experience, enthusiasm and commitment of the lecturing team. Patients seem as equally delighted with this one-day opportunity to gain understanding of their problems, coping mechanisms and practical advice as did their predecessors attending the two-day session. From all the foregoing experiences in Back Care Education, it is concluded that one full day is the very minimum time necessary for the retention of the comprehensiveness of the Programme for our military patients. It is speculated that to sacrifice any of the present content in the interests of time economy for any reason, would seriously affect its holism, quality and effectiveness, though even a three-hour back school has been described as a "positive" experience.[16]

Data Processing Difficulties

Data Processing Services for the Questionnaires were obtained from the Canadian Back Education Unit between 1978-1980. Thereafter financial constraints precluded any further processing until Nov 1984. Consequently the Questionnaires from the years 1981-1984 were stored until this time when services were obtained from the University of Ottawa, a much closer source. Patient compliance for return of the Review

Questionnaire has always been difficult. Although 540 patients attended the BCEP in 1978-79, only 40% of these patients returned their Review Questionnaires for comparison with their initial Questionnaires. In 1980, of 530 patients who attended, only 43% of Reviews were obtained. Between 1981 and 1984, 705 Reviews were sent out and 44% were returned. To provide encouragement with return, patients have been, since 1980, supplied with stamped and addressed return envelopes and an encouraging letter. A further difficulty was encountered; of those who did take the trouble to return their Review Questionnaires, a high proportion did not answer all the relevant questions making data processing for statistical significance of certain factors extremely difficult if not impossible.

Measuring the Value of the BCEP

Attempting to measure the worthiness of the BCEP has been a formidable task, as this is necessarily a very subjective measure. The questions asked on the Questionnaires designed in the early seventies provide a great deal of very interesting information, possibly useful for future research purposes, but were not found to be specific enough for an analysis of improvement which could be attributed entirely to Back Care Education exclusive of other treatment received. It is anticipated that such a measure would be possible under pure research conditions. The results obtained to date are shown in Table 3.

Table 3

General Status At Six-Month Review

Percentage Rated Factor	1978-79 +	1980 +	1981	1982	1983	1984	1981-84	Average Improvement
1. % Pain Getting Worse:								
Before BCEP			19.6	16.6	26.0	21.8	19.33	
After BCEP			4.5	16.3	55.0*	2.0	7.6 (1983 not included)	60.73
2. % Cont. Pain Without Attacks:								
Before BCEP			14.7	19.1	21.4	19.0	18.55	
After BCEP	15.0		16.0	15.0	16.8	20.3	17.0	8.35
3. % Cont. Pain With Attacks:								
Before BCEP			16.4	14.0	22.8	33.3	21.63	
After BCEP			7.0	9.5	12.1	7.8	9.1	57.92
4. % Required No Further Treatment i.e. After BCEP	70.0	79.0	70.1	67.0	71.4	** 57.1	71.50 (1984 not included)	
5. % Following Back Care Regime:								
Before BCEP			74.6	74.2	90.9	90.1	82.45	
After BCEP			86.5	87.3	95.0	97.0	91.45	10.9
6. % Found BCEP Helpful:	95.0	95.0	95.0	91.0	97.0	100.0	95.75	
7. % Rated Themselves						***		
Improved:	76.0	73.0	74.0	72.7	71.0	88.2	73.34	
Not Improved:	24.0	27.0	26.0	27.3	23.0	11.8	25.46 (1984 not included)	

* An anomaly, reasons for this are being explored.

** Lower percentage explained by higher percentage of patients undergoing Physical Therapy Treatment at time of attendance at BCEP and continuing treatment immediately afterwards.

*** 4 months of the One-Day programme recorded in the 1984 statistics.

\+ Statistical data for 1978-80 received from the original source of Data Processing Services were extremely scanty.

These results provide an indication of the value of education and were obtained from the answers provided to the following questions:

1. Do you think your back pain is getting worse?
   (Percentage noted for those answering yes before and after education - The difference is indicative of ability to prevent or control pain).
2. Do you have continuous pain without attacks in addition to your pain?
   (Percentages for those answering Yes calculated before and after education

   - the difference is indicative of ability to prevent attacks).
3. Do you have continuous pain with attacks in addition to your pain? (Percentage for those answering Yes calculated before and after education - the difference is indicative of ability to control attacks).
4. Have you received any further treatment in the last six months, i.e. following the BCEP? (Percentage noted for those not having required treatment - an indication of non-recurrence in a six-month period).
5. Are you following a Back Care Regime now, i.e. regular exercise, behaviour modification, modified lifestyle, postural control, etc.? (Percentage noted for those answering Yes - an indication of assimilation of the BCEP content).
6. Did you find the BCEP helpful to you? (Percentage noted for those answering Yes - an indication of the usefulness of the BCEP).
7. How would you rate the condition of your back now, i.e. since attending the BCEP? (Percentage Satisfactory = Grades 3, 4 and 5; Unsatisfactory = Grades 0, 1 and 2
   - some indication of effectiveness of BCEP but inconclusive; too many other factors).

Activity Limitations

Patients were also asked if they had any limitations in the following Activities of Daily Living: sitting; standing; walking; driving; general exercise; gardening; lifting; carrying; sexual intercourse; housework; lying down; sleeping, and sports. At Review, they were asked if they still had limitations in the practice of these same activities. The activities identified as producing greatest limitation by the majority of those who answered this series of questions included Sitting; Standing; Lifting; Carrying; and Sports. These activities, with the exception of Standing, were found to be significantly improved at the time of Review. These findings are shown in Table 4.

Table 4

Activity Limitations At Six-Month Review

% Activity Limited	1981	1982	1983	1984	Average 1981-1984	Percentage Improvement
1. Sitting:						
Before BCEP	35.0	41.1	41.0	44.2	40.32	
After BCEP	25.0	31.1	47.6	13.5	29.30	27.33
2. Standing:						
Before BCEP	27.1	31.3	41.0	51.6	37.75	
After BCEP	34.5	35.4	69.1	24.5	40.87	(8.26)*
3. Lifting:						
Before BCEP	43.1	56.9	63.0	67.2	57.55	
After BCEP	34.0	35.8	41.1	32.6	35.87	37.67
4. Carrying:						
Before BCEP	42.5	53.8	58.4	66.6	55.32	
After BCEP	41.4	38.7	32.5	30.2	35.70	35.47
5. Sports:						
Before BCEP	44.0	54.6	60.9	55.1	53.65	
After BCEP	32.6	37.2	28.5	24.3	30.65	42.87

* The reasons for more patients reporting limited ability to stand are at present obscure and may include a number of factors such as interpretation of pain, non-practice of postural control and fatigue- relief postures, weight-related factors, change in activity, etc. These results imply that the lecturing staff need to provide more attention to the postural control of pain in standing.

Overall Results

The overall results demonstrating effectiveness and usefulness of the BCEP may be measured in relation to the following factors: Pain, Activity Limitation, Performance of Back Care Regime, Requirement for no further medical treatment, the patient's self-rating of satisfactory improvement, and the helpfulness of the BCEP.

Table 5

Results

Factor	Before	After	Improvement
1. Pain:			
a. Pain Getting Worse (without 1983 statistics)	19.33%	7.6%	60.7%
b. Continuous Pain Without Attacks	18.55%	17.0%	8.35%
c. Continuous Pain With Attacks	21.63%	9.1%	57.92%
2. Activity Limitation:			
a. Sitting	40.32%	29.30%	27.33%
b. Standing	37.75%	40.87%	(8.26%)
c. Lifting	57.55%	35.87%	37.66%
d. Carrying	55.32%	35.70%	35.47%
e. Sports	53.65%	30.65%	42.87%
3. Performance of Back Care Regime:	82.45%	91.45%	10.9%
4. Requiring No Further Treatment: (1984 statistics not included)		71.5%	
5. Rating of Improvement:			
Satisfactory		73.34%	
Not Satisfactory		25.46%	
6. Found the BCEP helpful:		95.75%	

Interpretation of Results

As far as the effectiveness of the BCEP is concerned, the results shown do demonstrate that:

1. the BCEP does substantially prevent pain from getting worse (i.e. the frequency of episodic pain);
2. the BCEP does result in some pain reduction, (i.e. the intensity of pain).
3. the BCEP is very effective in reducing successive attacks (recurrences).
4. the BCEP does result in reducing limitation in the activities of sitting, lifting, carrying and sports. That more patients at Review reported limitation for standing requires investigation.
5. the BCEP does result in an improvement in the performance of a Back Care Regime, and there appears to be a relationship between those who consciously care for their backs and the reduced frequency of pain and attacks. The Back Care Regime consists of regular, modified, or restricted exercise; modification of general activity; the avoidance of certain activities if necessary; change in posture; behaviour modification; regular medication and use of a back brace if necessary. Of the high percentage of patients reported carrying out a back care regime prior to attending the BCEP, most indicated that they performed exercises only. At Review the majority still performed regular exercise but included modification of activity, postural consciousness, and behaviour modification.
6. that the BCEP has reduced the requirement for further treatment for 71.5% of patients at the 6-month review would be more meaningful had these patients been surveyed at an interval of one year.
7. That the BCEP has been entirely responsible for the satisfactory improvement of these patients cannot be wholly determined unless control groups not receiving education and receiving education only can be included.
8. that the usefulness of the BCEP to these patients is undoubted.

Length of the BCEP and Overall Effectiveness

There appears to be little or no relation between the length of the Programme (5-day, 2-day, or 1-day) and (a) the frequency of continuous pain or attacks, and (b) the requirement for further treatment. However, when the patients rate their degree of satisfactory improvement following the BCEP, while there is no difference between the five and two-day Programme (1978-1983), 1984 presents the first significant difference (Table 3) which may be the result of the inclusion of four months of the 1-day Programme so far recorded. The 1985 data will be better able to demonstrate this when processed by the end of 1985.

Comments by Patients

The Questionnaires at Review provide space for comments by the patients. Some patients include letters as well, describing their modifications in the conduct of their activities, and lessened intensity of pain; a few have stated that the knowledge obtained in the BCEP has actually eliminated their pain, most probably through the alleviation of anxiety. All letters and comments have expressed gratitude, including comments such as: "This is the best military course I have ever attended;" "Why couldn't all of this have been taught me twenty years ago?" (the author never insists that they would not have listened quite as attentively twenty years ago). "Everybody at Recruit School should have this education - think of all the problems I wouldn't have had to suffer...", etc. etc. All patients are invited to write or telephone if they have any particular problems that they feel they need specific help or advice to cope with them satisfactorily. And they do, with problems ranging from obtaining a comfortable night's sleep on cold, uneven ground during field exercises to working in necessarily awkward positions on aircraft. Others write to request that they share newfound experiences less traumatic to the spine with future classes. What is most gratifying is that all these "graduates" appear to regard the BCEP as a resource now where they can turn to for advice at any time in their careers with regard to their back problems.

All patients with unsatisfactory ratings, i.e. those who grade themselves as being worse, or showing no perceptible change in their condition, or who write to express concern with an increasing problem, are invited back to the Department for reassessment, and further investigation by the Chief of Orthopaedics if necessary, and appropriate treatment. A small percentage of the more serious cases, for instance, those with metastatic tumours, have been identified this way. Others have merely required more Physical Therapy treatment and refresher courses, and a minute number have simply been reluctant or unable to modify behaviour or activities and have preferred not to part with their longstanding, companionable pain, nor with their TENS Units. This minority invariably comprises Veteran patients in their late sixties.

Cost Effectiveness of the BCEP

The cost effectiveness of the prevention of recurrent back injury is based on the cost of time lost due to absence from work versus the cost of education of the patient. It is extremely difficult at present to determine the frequency of recurrent injury following a first-time incident of Low Back Pain owing to lack of specificity of data. For present purposes, although 60% of those suffering a first-time incidence can be expected to have recurrent episodes[3], without the benefit of preventive education, the NDMC experience has demonstrated that 71.5% (Table 5) have not required further treatment following education.

Based on an everage of 300 patients per year attending the BCEP for one day, at a cost of $600 per member to the Department, the programme costs $180,000 per year. Since a disabling back injury in the CAF requires an average of 5.13 days' absence from work[19], the cost to the Department for recurrent episodes in 60% of these patients were they not educated would amount to $554,040. However, following the BCEP, 71.5% or 215 persons have not required treatment. The 85 persons who may be assumed to have experienced recurrence, have cost the Department $ 261,630. Therefore, based on a potential loss of $554,040 per year to the Department, the BCEP at the NDMC has saved the Department $292,410 (excluding any required treatment costs) at a cost effectiveness of 1.62 per year.

This disregards the probability that the frequency of third, fourth or fifth recurrences is higher than the 60% of recurrences expected after a first episode. It should be noted that the majority of patients referred to the BCEP have already experienced a recurrence, and that the percentage of re-reoccurence is higher than that of the first recurrence and therefore greater than 60%. It also disregards more than one recurrence per patient. The cost effectiveness of 1.62 can therefore be considered an absolute minimum; it is probable that this ratio can be shown to be in access of 3 or 4:1 with better data from the field. This is already being addressed in the latest questionnaires. It is speculated that the savings to the Department of National Defence could be considerable were it possible to extend the BCEP to all Bases, Stations and Ships, and to include the DND Civilians as well.

Conclusion

1. The BCEP at the NDMC has proven effective in preventing the present condition from becoming worse, in reducing the intensity of continuous pain, and in controlling recurrent attacks of Low Back Pain. It has also proven effective in reducing activity limitation in lifting, carrying, sitting and sports.
2. The BCEP has encouraged more clientele (91.5%) to be responsible for the care of their backs in following a regime of regular exercise, activity modification, behaviour modification and postural control. Patients, almost unanimously (95.75%) recognize and appreciate the benefits received.
3. There is little demonstrable difference in outcome between a 10-hour course conducted over five days, the 8.5-hour course over two days, and the present course of 7 hours conducted in one day.

4. The BCEP is a cost effective mechanism to increase the overall effectiveness of DND personnel by reducing the number of days lost due to recurrent back injury and back pain.

Back Care Education at the National Defence Medical Centre is a continuing process. The collection and analysis of patient data will continue in order to determine responses to increased or changed patient needs, and to continuously assure high quality standards and cost effectiveness. All patients attending the 1985 sessions and thereafter will be reviewed for one year for better data.

From September 1985 the session on the Modification of Activities of Daily Living conducted by the staff of the Occupational Therapy Division will be an entirely practical session. The need for practical participation by clientele has been based on the observation that patients with recurrent Low Back Pain attending the classes have little concept of the degree of hip and knee flexion required for some daily activities.

It has also been observed in the Exercise Session that those with longstanding Low Back Pain demonstrate weakness of the abdominal muscles, quadriceps and gluteii, as well as tightness of ilio-psoas, rectus femoris, erector spinae, hamstrings, piriformis, and other muscle groups. This observation may result in the development of a twelve-session Back Exercise class, as part of complete Back Care for clientele at the National Defence Medical Centre.

The response from the educated patients is conclusively positive and encouraging. It can therefore be concluded that education must continue as an integral part of the holistic treatment of all patients with mechanical low back disorders, and that it would be advisable to expand this service to a wider range of departmental employees, military and civilian.

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DISCUSSION

LANDOLT, CA: In regard to crewmen, your presentation discusses the vulnerability of tank crewmen to back injuries and their severity. Have you comparable statistics for different air crewmen? If so, how effective is your Back Care Programme in returning them to work?

WARRINGTON-KEARSLEY, CA: It was very difficult getting any information on aircrew. I had gone to our Director of General Safety to see what sort of data had been submitted to him. Unfortunately, we did not have very much on aircrew. Out of the 10 who had been reported as suffering from disabling back injury within a 5 year period, 9 were pilots and one was an air navigator. They were mainly student fighter pilots, who were taking the Basic Officer Training Course in British Columbia. None had suffered their injuries in aircraft or within their flying duty area; they had suffered sports injuries. So, its extremely difficult to provide details in this area. A lot our pilots have described back pain, but none of them have been reported officially to the Directorate of General Safety. In the Back Care Programme we can only teach them how to avoid further recurrent injury as far as their own actions and postural activities are concerned. A lot of these people have asked if they can wear back braces or apply a back support to the aircraft seat.

LANDOLT, CA: Why did you remove the deep relaxation session from your one-day programme? That technique and biofeedback have been quite successful in returning air crew to duty from air sickness. You used it in your other programmes.

WARRINGTON-KEARSLEY, CA: The reason is that, within the short period for back care education, the only time that we could afford for deep relaxation is one hour. Now, when you have a class of 16 people, all attempting to practice deep relaxation or at least be introduced to the technique, half the class will promptly fall asleep and begin to snore, which disturbs the other half of the class who are desperately trying to relax. All of our deep relaxation sessions were an absolute failure. Consequently, we decided that the physical therapists would then treat all these patients with individual deep relaxation sessions and give them a first-time session. After that, they were issued cassette tapes that they could take and practice in the peace and quiet of their own homes.

WILDER, US: Is there an average job description of the cooks who were in the program? Are they carrying great tubs of potatoes or similar heavy objects?

WARRINGTON-KEARSLEY, CA: Yes, the cooks were obviously in the high risk group; and it's very interesting that, when you teach people how to lift things correctly, you generally teach them to keep a very straight back and to bring the object closer to their own center of gravity. Now, in the case of the cooks, it's very difficult to do this because, half the time, if they are field cooks for instance, they are carrying great pots of soup or stew or whatever -- enormous trays of very hot food, which you cannot bring close to your center of gravity. So I would think that, by having to suspend these large objects at the ends of the arms, they are subjecting the lumbar spine to enormous shear forces. This may be a reason; in fact, this is what I suspect may be the reason for the severity of injuries to our cooks. The other factor may be the floors, on which cooks may have to tread fairly carefully. There are sometimes spills; they are not always dry; and they are not always non-skid surfaces. Perhaps, this total area needs to be investigated more closely.

POSTURAL FATIGUE
AND THE BACKACHE OF HELICOPTER PILOTS

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Summary

A review of the literature on the back pain of helicopter pilots suggests that postural fatigue, rather than specific injury to the spine, may be the cause of much of the reported pain. Postural fatigue is defined here as fatigue in specific muscles whose continuous activity is required to maintain a working posture. Descriptions of the back pain of helicopter pilots are compared with those of the phenomenon of postural fatigue. It is significant that there is a strong association between the pilot's back pain and actual flight duty, in fact, pilots often blame their helicopters, rather than their own health, for their pain. Biomechanical aspects of the pilot's environment and of tasks within the cockpit are assessed as potential causes of postural fatigue. Both posture and vibration within the cockpit may be possible causes, since both conditions may impose continuous activity on muscles of the lower back. Postural fatigue is a temporary problem, but the causes of postural fatigue, such as sedentary work in awkward postures, are considered by many authors to be related to increased incidence of chronic back pain, back disease and related disability. Repeated exposure to postural fatigue may increase the likelihood of mechanical back injury by reducing the effectiveness of the protection given to the spine by its supporting muscles during tasks involving bending and lifting. Electromyography has been used to index postural fatigue in the laboratory, as well as in the civilian work environment. By objectively defining muscle activity and fatigue, electromyographic methods may allow the objective assessment of different ergonomic proposals to relieve the back pain in helicopter pilots.

The Back Pain of Helicopter Pilots

For about a quarter-century, the medical authorities of many armed services have described the phenomenon of pain in the lower back among helicopter aircrew [1]. The most comprehensive review of this problem is the chapter by Delahaye and his co-authors [2] in the book: "Physiology and Pathophysiology of Spinal Injuries in Aerospace Medicine." (I have used the English title of the translation by P. Howard.) These authors describe the phenomenon as follows:

> "Chronic lumbar pain is the most common complaint. The picture is of a low-grade, tiring, heavy ache localized in the lumbar region, or sometimes lower (lumbo-sacral pain). It extends laterally, often predominantly to one side, and may radiate to the buttocks, the iliac crests or, more rarely, the groin. This discomfort is brought on by flight, aggravated by lifting effort or by long car journeys, and relieved by lying down and by physiotherapy.
>
> At a higher level of intensity, this discomfort becomes a pain which makes flying very gruelling so that, despite the constraints upon the position of his limbs, the pilot seeks to change his posture. The pain increases in intensity during the last flight at the end of the day, and reaches a maximum when the pilot lands the aircraft. Although it persists during the evening, it tends to diminish, but reappears on standing. It disappears after a night's rest."

The severity and prevalence of the problem called "idiopathic low-back pain" is widely known. It ranks among the more common reasons for seeking medical help in the industrialized countries. Back disorders in general are an important cause of worker disability. Thus, the words "backache", "low-back pain", or the many synonyms for this condition, call to mind a chronic condition associated with considerable pain and costs.

The relationship between the problems of a helicopter pilot and the common phenomenon of idiopathic low-back pain is an important question. Is the problem of back pain in aircrew, which has been reported and discussed so frequently by military authorities, the same as the problem which costs the civilian population so much in medical treatment, lost time, and compensation?

The description of the helicopter pilot's complaint quoted above from Delahaye et al. [2] resembles the description given of idiopathic low-back pain given in

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text-books on the subject, such as that by Finneson [3]. However, there are some differences between the two phenomena which are worth mentioning. Shanahan [4], in a recent lecture, has observed that the incidence of back pain in the civilian population, although high for a disease, is much less than the reported incidence of back pain in surveys of helicopter aircrew, which sometimes reaches 100%. The other significant characteristic of the helicopter pilot back pain problem is its strong association with actual flight duty.

Back pain in the civilian population is usually reported to medical professionals by patients who have suffered chronic pain for many days. Although there are some patients in which a rapid onset of pain is associated with a particular activity, such as bending or lifting, there are many patients who cannot remember the occasion of the onset of their pain [5].

In contrast, the helicopter pilot's back pain is closely associated with actual flight duty. Fitzgerald and Crotty [6], in a general survey of aircrew and groundcrew in the UK Royal Air Force, found that over half of the 300 pilots who experienced frequent in-flight backache never suffered from backache on the ground. In a previous AGARD conference, Schulte-Wintrop and Knoche of the Federal Republic of Germany reported on a survey of 145 helicopter aircrew that 40% complained of back pain during flight and 51% of back pain after flight. In only 39% of the cases, the back pain was described as a lasting one.

Shanahan [4] reported on a survey of 802 U. S. Army aviators which found that 72.8% experienced back pain while on flight duty, while only 14.5% had symptoms which persisted longer than 48 hours. Singh [7] reported that all of a group of 21 Chetak pilots in the Indian Air Force experienced back pain in flight, but this was relieved in all cases by rest.

There has not been a formal survey of Canadian helicopter pilots published recently, but informal reports indicate that there is also a strong association between back pain and actual flight duty in Canadian Forces pilots.

All these results suggest the conclusion proposed by Shanahan [4]: there are two groups of pilots who suffer from back pain, a majority who suffer a temporary pain which is felt only during and immediately after flight, and a minority who suffer from chronic pain, which resembles the problem known as idiopathic low-back pain in the civilian world.

Shanahan proposes that repeated exposures to the temporary pains of flight may lead to persistent pain in time. It is *probably premature* at this time to say that helicopter flight duty is a proven risk factor in chronic low back pain or the related disorders, such as herniated intervertebral disks or sciatica. However, the fact that similar activities in the civilian population, such as professional driving, are proven risk factors [8] suggests that this may well be the case.

The temporary pain associated with flight should not be ignored. Many authors, and some pilots, acknowledge that it may induce a pilot to modify his flight plans or distract him from his mission. It may be a more significant problem for the military use of helicopters at a future time when helicopters are required to play a greater role in military operations and longer and more arduous missions are undertaken.

It is also likely that, through understanding the temporary pain, better knowledge of the causes of the chronic pain may be obtained.

Given that the temporary back pain of helicopter pilots is a phenomenon and operational problem in itself, how can we most easily understand its causes and provide relief for the afflicted pilots? This essay proposes that the pain arises from postural fatigue. This hypothesis is not new; the concept of fatigue as the source of discomfort in helicopter pilots has been mentioned by other authors [5,7,9,10]. It deserves some examination in detail, both as a focus for future research and as a guide to those who are attempting to relieve the problem.

Postural Fatigue

"Postural fatigue" is the condition which arises when an awkward posture is maintained for a long time. Arndt [11] describes the phenomenon, as experienced by video display operators, as follows:

> "While the amount of effort required to maintain the various postures involved in (video display terminal) work depends on the position of the trunk, the limbs and the head, the maximum capacity of the musculoskeletal system is ordinarily not approached, even in the most extreme positions. However, such jobs often involve prolonged periods of constrained posture characterized by static loading of muscles. Under such conditions, blood circulation may be reduced, preventing the proper supply of nutrients to the muscles and removal of muscle activity by-products, leading to rapid fatigue and pain. If these conditions persist on a daily basis, the result may be chronic problems often including the joints and tendons."

A number of investigators have reported on the temporary discomfort caused by the maintenance of awkward postures, without describing the phenomenon as fatigue. The source of discomfort may be the sustained stress on joints, ligaments or tendons, which may create discomfort through interference with normal blood flow and nutrition of tissues [12].

Postural fatigue appears to be distinct from the muscle fatigue induced by strong contractions in that:

a. the muscles involved are active at levels which are a small fraction of the maximum voluntary contraction force;

b. the evidence of fatigue is muscle pain, rather than the diminution of force (which is the criterion given by Edwards [13], among others); and

c. the fatigue takes a much longer time to occur than is usually the case in studies of sustained contractions.

Muscle fatigue is a complex phenomenon, in which different causes (force, duration, duty cycle, blood flow, muscle type and motivation) play a part, and many different effects (reduction in maximum force, pain, stiffness) are produced. Physiologists have studied the relationship between the causes and effects of this phenomenon extensively for many years. A CIBA foundation symposium [13] provides a summary of recent research. Most studies have examined the effect of relatively brief, nearly maximal contractions or exercises on the performance of individual muscles.

One phenomenon of relevance to the study of postural fatigue is the "low-frequency fatigue" described by Jones [14] and by Edwards [15]. This is induced after a long series of ischaemic contractions and persists for several hours, as a reduction in the force response to nerve stimulation at frequencies less than that required for the production of the maximum tetanic force. The cause of the slow recovery is believed to be damage to the internal tubule system of the muscle. The association between this fatigue and pain is not described by these authors.

Other authors attribute the temporary pain associated with sustained contractions to the accumulation of lactic acid or other products of muscle metabolism. The relationship between the pain associated with fatigue and impairment of blood flow has been mentioned by several authors [16-18]. The impairment of blood flow appears to be as significant a factor in the development of pain as the actual exertion of the muscles. This impairment can arise either from external pressure or the internal pressure developed in an active muscle [19,20].

The development of fatigue in sustained muscular contractions and the process of recovery have been studied by Monod and his colleagues (as reviewed by Monod [21]) and by Rohmert [22,23]. The application of their findings to postural studies has been discussed by Corlett [24] and by Corlett and Manenica [25]. There is some disagreement about the effect of contractions which are a small fraction (less than 10%) of the maximum voluntary contraction (MVC). Whereas Monod and Rohmert suggest that there is a "critical force", about 15% of the MVC, below which an exertion can be held for an indefinite time, Corlett states that the "critical force" is no more that 8% of the MVC, and suggests a definition of "indefinite" which "restricts it to about 30 minutes" [24]. This disagreement probably arises from the behaviour of different muscle groups, as well as the difficulty in measuring the effect of a small contraction held over a long period of time. Corlett's observations apply more specifically to the muscles of the lower back.

The Use of Electromyography in Determining Postural Fatigue

Electromyography has become a method of choice for investigation of the effects of awkward postures and the development of postural fatigue. Earlier investigators used the simple amplitude of the electromyographic (EMG) signal to estimate the level of activity in the back muscles [26-30]. This is valuable for estimating the force produced by a muscle group, and, indirectly, the stress on associated joints and ligaments. It has been used this way in studies of biomechanical models of the spine by Nachemson [31], and by Andersson and his colleagues [32-38]. The relationship between the EMG signal amplitude and muscle force is not an exactly linear one in all cases, as noted by Grieve and Pheasant [39]. However, if the posture of the subject and the length of the muscle under study are controlled, the EMG signal is a good relative index of muscular force.

It has been known for some time that there are changes in the electromyogram which are associated with muscle fatigue: (see the review by Lindstrom and Petersen [40]) and, in the last fifteen years, the computer analysis of electromyograms has allowed the routine application of techniques which use this phenomenon. The principal change in the EMG signal is a shift in the frequency spectrum towards lower frequencies [40-43]. This can be measured as a shift in the mean power frequency, as described by Lindstrom et al., [44,45] or as a shift in the median power frequency as described by de Luca and others [46-48].

A reason given for the change in the EMG spectrum is a change in the conduction velocity of action potentials in the muscle fibres; this is likely to be the consequence of changes in the membrane or internal tubule system caused by the accumulation of metabolites [49,50]. The changes in the EMG signal precede the development of pain in some muscles [41].

There are now many examples of the use of electromyography to demonstrate the fatigue caused by sustaining awkward postures. Andersson et al. [18] demonstrated the increased EMG activity in the back muscles of automotive assembly workers. Herberts and Kadefors [12] used the EMG technique to study the shoulder pains of welders in the shipbuilding trade; they have to hold their arms above their shoulders while performing welding tasks. More recent studies show that this posture leads to rapid fatigue [51], and increased intramuscular pressure in certain muscles of the shoulder. [52] Malmqvist et al. [53] has shown the same phenomenon in certain building trades, and Magunsson et al. [54] have shown it among butchers.

Postural Fatigue in the Helicopter Pilot

Delahaye and his colleagues [2] identify two potential causes of back pain in helicopter pilots: the posture of the pilot in the cock-pit and the vibration of the helicopter. Most investigators agree on the importance of one or the other of these causes. Whether posture or vibration alone can be considered as the major cause is not yet answered, and the relative importance of these causes will be an important topic for discussion at this meeting.

Three important aspects of the posture of a helicopter pilot appear to be principal factors in the genesis of low-back pain. They are:

a. the "helicopter hunch", the forward-leaning posture required in order to place the right elbow on the thigh for precise positioning of the cyclic control stick;

b. a twisting or bending of the trunk in order to reach the collective lever (this may be unnecessary for some pilots in some helicopters); and

c. the fact that all four limbs are engaged in the control task, permitting no change of the posture during the period when the pilot is in actual control of the aircraft.

Other factors identified as contributing to discomfort and pain are, the requirement to extend the neck for normal forward viewing while holding the "hunched" posture, stresses from backpacks or seat restraint systems on the upper back, thermal stresses (particularly, exposure to cold drafts [7,55]) and the natural tension created by involvement in a difficult task.

Individual seat and control designs can aggravate the postural stress. In particular, seats without adequate lumbar support and cockpits without adequate head clearance [56] can prevent the pilot from assuming a relaxed posture even when control is passed over to the co-pilot.

It is important to note that each of the above-named postural causes of discomfort is associated with increased activity in major muscle groups in the trunk.

The increase in muscular activity in the erector spinae muscles of a person who leans forward while sitting is well documented [32,37]. Similarly, the maintenance of a twisted or leaning posture has been shown to require extra muscular activity in the lower back [28,57].

The fact that the pilot cannot easily change his position while he is in control of the aircraft implies that the stress on postural muscles is often maintained for longer periods than is desirable. The pressure caused by muscular action and the pressure on the back and buttocks from the seat impair blood flow and accelerate the development of fatigue.

Troup [58] has noted that the psoas muscle which originates in the lumbar spine, is used by truck drivers every time they lift a foot from a pedal. Thus, continuous activity of the feet on the pedals may require continuous activity of the psoas muscle, and consequent fatigue. Helicopter pilots should be at least as vulnerable to this effect as truck drivers.

The development of muscle fatigue in the back muscles will be accelerated if the pilot is exposed to a high workload. Activity of back muscles increases during concentration at work [59] and has, in itself, been used as a measure of workload-induced stress [60].

Whole-body vibration has been understood to be a source of discomfort for many years. The vibration of helicopter cockpits has been identified by some authors, including Delahaye and his colleagues [2], as a significant factor in the genesis of pilot back pain. The International Organization for Standardization Guide for the evaluation of human exposure to vibration (ISO-2631) [61] includes a "fatigue-decreased proficiency" boundary to tolerable vibration limits. The "fatigue-decreased proficiency" boundary was considered by those drafting the guide to be the intensity of vibration above which the preservation of working efficiency would be threatened [61]. Although this limit is the subject of some controversy, there is some evidence that muscular fatigue increases with vibration exposure [62].

Several authors have studied the response of the back muscles to vertical whole-body vibration, and have shown that there is activity in these muscles which is in step with the applied vibration at lower frequencies [63-65]. This activity could be the response of the stretch reflex to changes in body geometry caused by the different response of the pelvis and upper torso to the applied forces. Recent results from Bluthner et al. [66] suggest that this response may not be effective in attenuating vibration. In any case, the activity must contribute to fatigue.

In addition to the direct response to vibration, there is also the possibility that the human subject may use his muscles to stiffen his torso against the effects of vertical vibration. Griffin [67] explored this phenomenon, and found that a subject would naturally adjust his position and muscle tone in order to shift the resonant frequency of the body away from the frequency of the applied vibration. Vibration may also discourage the use of a seat back as a support for the body, since, as Rowlands [68] discovered, the seat back can affect the transmission of vibration to the head. These separate observations suggest that vibration exposure (and possibly exposure to the vibration of helicopters) increases the activity in the muscles of the back. Whether this is sufficient to cause fatigue, has not yet been answered in the literature.

All of this evidence indicates that the pilot of a helicopter is likely to show continuous activity in the muscles of his back as a consequence of the various stresses induced by the task and the cockpit environment. This activity will be sustained at least for the time that he is in control of the aircraft, and may persist for the duration of a flight. It will be accompanied by impairment of circulation from the external pressure of the seat and restraints, and possibly by local cooling of the muscle by cold drafts. All this should lead to a painful ischaemic fatigue, from which the muscles would, as Jones [14] noted, take hours to recover. Whether this is the cause of the helicopter pilot's back pain is now a matter of speculation. There is clearly an opportunity to study the posture and behaviour of the helicopter pilot with the same methods that have been applied to industrial workers who suffer from postural fatigue as a result of their workplace.

Postural Fatigue and Chronic Back Pain

Many authors have noted the epidemiological connections between occupations which demand awkward postures and chronic backache [8,58,69-74]. In the case of vehicle drivers and pilots, the effects of awkward posture are often complicated by the effects of vehicle vibration, which, as described above, may contribute to fatigue.

There are various hypotheses concerning the role of vibration and posture in the genesis of chronic back pain. The effects of mechanical loads have been reviewed by Sandover [75,76], who suggests that the stresses on the intervertebral discs and end-plates may cause local fatigue (in the engineering sense of the word) or impair the nutrition of the discs through the end-plates. In addition, the intervertebral disc loses height when exposed to compressive stress [77], particularly when vibration is superimposed on it. The bending postures which increase the muscular activity of the erector spinae muscles also increase the pressures in the intervertebral discs by proportionate amounts, so that the possibility of impaired nutrition or fatigue failure is increased. It is possible that these are the causes of the changes which are felt as chronic backache, however, it is difficult to test this hypothesis experimentally.

On the other hand, some investigators have suggested that there is a component of chronic back pain which is related to muscle function and muscle fatigue. Floyd and Silver [26], in their early electromyographic studies noted that patients with back pain showed no reduction in EMG activity in the lumbar erector spinae muscles during extreme forward bends, but healthy subjects did. De Vries [78], Troup and Chapman [79], and Jayasinghe [80] have sought evidence of increased fatiguability in the erector spinae muscle of patients with back pain. Suzuki and Endo [81] have found that patients with lowback pain are weaker in tests of maximal lumbar flexion and extension force than controls. However, this may be the consequence of a reflex response to back pain rather than a cause of the pain.

Another occupational risk factor for back pain and related diseases is heavy physical work [82-84]. Lifting, pushing and pulling often impose the largest stresses on the muscles as well as the intervertebral disks and these activities are often associated with sudden attacks of low back pain. It is possible that drivers and others who are exposed to postural fatigue of the back muscles may become more vulnerable to severe injury from lifting because of the weakening effect of their fatigue, which may last for several hours after the fatiguing posture is relieved.

Conclusions

It may never be possible to completely understand the mechanisms whereby the postural constraints and vibration of the helicopter cockpit can induce either the temporary back pain associated with actual flight duty, or chronic back pain in the helicopter pilot. It appears inevitable that forces transmitted through the body will be shared by muscles as well as ligaments and joints. Therefore, all of these organs will show the effects of chronic exposure to stress. Similarly, the activity of postural muscles, whatever causes it, will impose additional stresses on tendons and joints.

The intent of this article was to focus attention on muscle fatigue as a cause of helicopter pilot back pain. The most prevalent form of back pain among helicopter aircrew is a temporary pain which is brought about by actual flight duty and relieved by rest afterwards. This resembles, at least in its time course, the effects of muscular fatigue. There is indirect evidence that the back muscles of an active helicopter pilot must be more active than normal and that they may also suffer from impaired circulation. Thus, it is possible that flight duty can bring on this localized fatigue.

This argument does require further research, if it is to be supported or refuted. Quantitative studies of the posture and activities of pilots in flight should be made in order to determine how much activity is produced in the muscles of the lower back and how much fatigue is produced by this activity. It is possible to do this using electromyography, and Pope and his colleagues [65,85] have approached this in their studies on vibration. The pressure within the muscles and the effective blood flow might also be measured.

How does the concept of postural fatigue affect those involved in designing helicopters and planning the use of helicopters in combat and other military operations? There is now an intense research and development effort directed towards making helicopters (and other aircraft) easier to fly in complex operational situations. Stability-augmentation systems eliminate much of the work required for simple attitude control. The workload can be further reduced by improved controls and displays. Ergonomists have defined better criteria for the positions of the cyclic and collective controls [86].

A more radical approach to helicopter controls is being pursued by authorities in the United States and Canada, where multi-axis side-arm control designs are being flight tested in experimental helicopters [87-89]. Preliminary studies of these controls indicate that the associated arm rest, and the improved back posture, lead to a great reduction in the back pain induced by actual flight (J. M. Morgan, personal communication).

At the same time, helicopter vibration reduction has been an important goal in new aircraft designs [90,91]. Vibration-attenuating seats and cushions are also being developed, in order to improve the comfort of those pilots who must contend with the current helicopters of our armed services [92,93].

In addition, new seat designs, or modifications to existing seats, are being proposed for many helicopters in order to improve the lumbar support offered by the seat and the comfort of the seat pan [7,94].

The cumulative effect of these improvements may be that the incidence of back pain associated with helicopter flight duty may be reduced, or that the permissible flight duty periods may be extended. However, design engineers, who have to work with the constrants of crashworthiness, restraint for the pilot, reduction in weight and other limitations, may be tempted to choose a single "ideal" posture for the pilot of a future helicopter, and suit their designs to this one position. In doing this they may fail to allow any changes in posture during flight, whether or not the aircrew member is in actual control of the aircraft.

Studies of postural fatigue and seated posture have emphasised the importance of regular changes in the seated posture during the time that an individual is seated [95,96]. It is not unrealistic to state that even the most comfortable seat may become a "torture-chamber" if one is forced to occupy it in a fixed position for an extended period. Pressure, whether from surfaces external to the body or from active muscles, must be relieved periodically, or the impairment of blood flow will lead to fatigue and pain.

One can see the potential for postural fatigue in proposals for "heads-up" displays or visual pointing systems for weapons control which demand a fixed eye-point for the pilot. Similarly, those who propose that the improved controls and seating of future helicopters will permit them to be flown by a single pilot [97], will have to consider the likelihood of postural fatigue, even in the most advanced cockpit.

However, if it is indeed true that the pain of muscle fatigue is a limiting factor in helicopter operations, there is the hope that a quantitative understanding of the process of fatigue and the need of muscles for rest will lead to prescriptions for work schedules which will make the maximum effective use of a helicopter pilot's abilities.

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Muscle Fatigue in Static and Vibrational Seating Environments

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Summary

In order to perform an objective assessment of muscle fatigue in a UH-1-H cockpit seating environment, instrumentation was developed to sense and use as an outcome measure the shift in the center frequency of the EMG spectrum of the dorsal lumbar musculature. Subjective assessment of fatigue was accomplished by means of a visual analog scale indicating discomfort as a function of duration of exposure to the seated environment. Twenty subjects (10 male and 10 female) were exposed to the same seating environment (in terms of both static posture and vibration exposure) as that experienced by the UH-1-H helicopter pilot. The vibration environment of a UH-1-H helicopter was recorded and reproduced using a servohydraulic vibration simulator. Each exposure lasted two hours.

Marginally significant fatigue, as measured by the center frequency shift method, occurred only as a result of the sustained static posture. In contrast, all exposures to this seating environment, in both static and vibration modes, produced significant subjective discomfort in both the buttocks and lower back. Thus, the predominant cause of back discomfort and fatigue in this instance appears to be the UH-1-H specific seated posture rather than the UH-1-H specific vibrational environment.

Introduction

The human spine is a complex mechanical structure which performs the dual task of motion production and load bearing. Since the bony spine is supported and moved by its surrounding muscular and ligamentous tissue, changes in their mechanical capacities could adversely affect the function of this system. Of great interest, then, is the response of the tissues to mechanically damaging environments. It is known from the work of Weisman, Pope and Johnson (1980) that repeated loading of ligaments in the knee makes the ligament mechanically softer (less stiff) and decreases its ultimate strength. Since it is difficult to measure changes of mechanical strength in lumbar ligamentous elements directly, monitoring behavior or strength changes in muscle would be very useful.

U.S. Army operational needs include minimizing low back pain production in UH-1-H helicopter pilots (Shanahan and Reading, 1984). Severe, acute and sometimes debilitating backaches have been reported by pilots of two-bladed helicopters. Vibration is probably a major contributor to the problem, but a lack of information on muscular tolerance to vibration and the role of vibration in fatigue makes a solution through appropriate equipment design exceedingly difficult. Chronic back ailments in aircrewmen having several thousand hours of flight experience deplete the aviation manpower resource and reduce its effectiveness. The cause of the ailments is thought to be vibration-induced damage to the spine. Data on joint morphology resulting from long-term exposure to vibration do not exist, yet are essential for establishing standards by which hazardous conditions might be limited. Vibration plays a significant role in the effectiveness of personnel in sophisticated systems, yet there is insufficient information to account adequately for human response in the design of such systems. Vibration is also known to affect health adversely. However, standards to not exist which relate vibration exposure in the military-unique envronment to these known hazards.

The present study was undertaken to develop methods for describing, objectively and subjectively, fatigue in the lower back and buttocks of subjects in a UH-1-H flight environment. To assess the effects of vibration in the Army rotary wing aviator, biomechanical data were gathered in order to address the following hypotheses:

(1) The biomechanical effects of helicopter vibration would be significantly modified by the posture of the aviator, as well as the layout of the controls, the cockpit, and the seat design.

(2) The effects of these vibrations would be sufficient to cause soft and hard tissue stress and subsequent injury.

Two test methods were used for these evaluations: (1) the shift of the center frequency of the spectrum of the lumbar musculature electromyography signal and (2) the subjects' subjective assessment of their discomfort in the lower back and buttocks by means of a visual analog scale.

Materials and Methods

Fatigue assessment via electromyographic activity. Shanahan and Reading (1984) have suggested that the problem of low back pain and discomfort reported by helicopter pilots stems from the necessity for pilots to assume slumped and asymmetric postures for extended periods of time with little chance to change their positions significantly. They have also suggested that this probably leads to spasm of paraspinal musculature and increased sensitivity of the buttocks.

In order to determine whether muscle electrical activity changes could indicate fatigue of the muscles, it was necessary to perform an initial study on a group of subjects who had no history of back pain. The experiments performed sought to find a change in the muscle response due to the sustained posture and vibration environment. Because a feature of muscle contraction is the production of a complex electrical signal arising from the summation of asynchronously firing muscle motor units, the muscle electrical activity or EMG signal can be monitored using surface or wire electrodes. In order to evaluate the complex EMG signal, a technique called spectral analysis was used to decompose the signal into its simpler components. Hence we were able to measure muscle electrical activity changes in a group of people exposed to this environment.

The subjects' lumbar electromyographic signals were picked up by means of bipolar surface electrodes placed at the L3 level approximately 3 cm lateral to the midline of the back 2.5 cm apart vertically and the silver-silver chloride electrodes 12.5 mm in diameter (In Vivo Metric Systems) were filled with a conductive gel that interfaced with the skin. The application site was lightly sanded and prepared with a skin conditioner ("Skin Cleaner," In Vivo Metric Systems item #E403) to maximize adhesion and conductivity. Because of variable torso sizes, it was felt that the protocol of Andersson, Jonsson and Ortengren (1974), that of placing the electrodes a set distance from midline, was inappropriate. Our modified technique of placing electrodes on the belly of the erector spinae muscle determined by palpation ensured a placement for maximum EMG signal amplitude. Interelectrode resistances were measured and ensured to be less than 5,000 ohms. Four channels of data were recorded (Figure 1) on a TEAC FM data recorder: left and right erector spinae EMG activity, RMS value of right EMG, and force as indicated by a load cell attached to a chest harness.

Since a correlation had been found between muscle force production and EMG activity (Andersson, Ortengren and Schultz, 1980), the next step was to evaluate the fatigue of the muscle via spectral analysis of the EMG signal. Previous workers (Lindstrom, Kadefors and Petersen, 1977; Lindstrom, Magnusson and Petersen, 1970; Lloyd, 1971; Petrofsky, 1980; Petrofsky, Dahms and Lind, 1975; Viitasalo and Komi, 1977) have shown that there is a change in muscle firing frequency before and after exertion. A spectrum analyzer was used to determine the shift of the center frequency of the EMG power spectrum density function (PSDF).

Twenty subjects were evaluated for their force versus EMG activity. Each subject was tested on each day over a six-day period. The first day of testing was a day of training for the subject to become acclimated to the test. Generally, the testing on each day consisted of monitoring the subject's EMG activity and force production during a maximum or percentage of maximum voluntary contraction (MVC). Subjects were seated (Figure 2) in a UH-1-H seat while wearing a seat belt and maintaining a femur-to-back angle of 70-80°. A chest harness was worn which transmitted horizontal forces from the torso to a vertical support. The force exerted was monitored by a load cell and displayed on a digital read-out so that the subject could see his force level and maintain a steady contraction. Prior to each day's fatigue test, three MVC efforts were performed in order to select the maximum as the 100% MVC. Subjects also held, for a few seconds, various percentages of their MVC (80, 60, 45, 37.5, 30).

Erector spinae muscle EMG activity was monitored before and after isometric extension tests. Typical EMG amplitude versus time signals are shown in Figures 3 and 4. Note that the "before" signal seems to be much more compressed, indicating a higher frequency than the "after" signal. Using the Wavetek/Rockland model #5820A spectrum analyzer, one can see in the power spectra (Figures 5 and 6) for these signals that there has indeed been a decreased signal from a higher to a lower frequency. It was this phenomenon of a decrease in the frequency of the EMG signal that was used to monitor muscle fatigue. Since the spectrum analyzer could communicate with the DEC 1123 minicomputer, an algorithm was written to compute the center frequency of the spectrum analyzed between one and two hundred Hertz. This is a single-number evaluation of the EMG spectrum, essentially the frequency at which the centroid of the plot area occurs.

Fatigue tests were conducted at one per day at either 80, 60, 45, 37.5, or 30 percent of the subject's initial Maximum Voluntary Contraction for that day. A constant force was held until exhaustion or until pain interrupted their isometric contraction (Figure 7). In summary, the following protocol was used:

Protocol: 3 maximum voluntary contractions (3 seconds)
80% MVC 5 seconds
60% MVC 5 seconds
45% MVC 5 seconds
37.5% MVC 5 seconds
30% MVC 5 seconds

All held for 5 seconds, with a 2-minute rest between
10-minute rest
Fatigue test to exhaustion - at one of the %MVC

Analysis of the EMG signal's spectral activity was determined over a 6-second period at the beginning and end of each fatiguing test. Using the index counter on a tape recorder and observing recorded EMG signals on an oscilloscope ensured that sampling occurred at the beginning and end of the test period.

Figures 8 through 11 show the results of the decrease in center frequency for the group of 20 subjects. Statistics were compiled for individual groups (males and females) for both left and right EMG center frequency decreases.

For all fatigue tests, center frequency decreased from the beginning to the end of the test. Comparisons were made between sides for the same sex and between sexes for the same side. The only significant difference (Figure 12) in changes occurred between sexes on each side at the 30% MVC level, where the females decreased in activity significantly less. The significance of this study derives from the demonstration that there is no difference in these changes either between sexes for the same side or between sides for the same sex except at the 30% MVC level.

Protocol of Static UH-1-H Cockpit Seating Tests. Subjects were seated in the UH-1-H seat and adjustments were made in seat height and distance to pedals in order to conform to the standard flight position of pilots. After placement of electrodes on the back, EMG signals were monitored to observe their amplitude and gains were adjusted to display an amplitude suitable for recording. Subjects were instructed in how to grasp the cyclic and collective and were told that they could remove the left hand from the collective for one minute every half hour. Instrumented into the cyclic were the controls for an Atari video game, which subjects were instructed to use in order to concentrate on a "mission."

One maximum voluntary contraction was performed to establish a 60% MVC contraction level to be used prior to and at the end of the two-hour seating test. The chest harness used for horizontal loading was the same as that used in the isometric fatigue study. It was removed during the two-hour seating test. The two-hour test period began when initial EMG signals were recorded (time = 0). Recordings were then made every 15 minutes for a total of nine samples. Also recorded was the time of onset of discomfort and level of discomfort at onset and at 15-minute periods following, using the visual analog scale (VAS) technique (Aitken, 1969). At the conclusion of two hours, the harness was reapplied and the 60% MVC was held to fatigue.

Protocol: Maximum Voluntary Contraction (MVC) - 60% MVC for 5 seconds
Sample EMG - time: 0, 15, 30, 45, 60, 75, 90, 105, 120 (minutes)
Record onset of discomfort and intensity of discomfort
60% MVC to fatigue

Vibration Seating Tests in the UH-1-H Cockpit. Twenty subjects were tested for a two-hour period on three different days in each mode of uni-axial vibration (up-down, fore-aft, side-to-side; Figure 13). EMG activity was recorded from the left erector spinae musculature and acceleration data were recorded from a bite bar accelerometer located on the mouthpiece and an accelerometer mounted on the actuator piston driving the seating system.

The protocol described for the static seating tests was followed throughout the two-hour vibration seating tests. Subjects were seated in the UH-1-H seat and adjustments were made to the seat height and distance to foot pedals to conform to the standard flight position of pilots. Subjects were instructed in how to grasp the cyclic and collective and were told that removal of the left hand from the collective was allowed for one minute every half hour. Subjects were instructed in the operation of the cyclic which had been instrumented to control the Atari video computer.

Prior to vibrating, a maximum voluntary contraction (MVC) was performed to establish a 60% MVC level to be used prior to and at the end of the two-hour tests. The chest harness was put on for the initial 60% MVC loading, removed during the two hours of vibration and reapplied for the final 60% MVC test. Four channels of data were recorded during the test: two channels of acceleration (bite bar and actuator), left erector spinae activity and reaction force at the actuator interface. Approximately every 15 minutes, data were sampled for a total of nine samples over each two-hour period. The accelerometer bite bar was inserted into the subject's mouth at 15-minute intervals to avoid fatigue of the mandible. Also recorded was the time of onset of discomfort and the initial level of discomfort, as indicated by the subject on a visual analog scale (VAS). Remaining 15-minute time periods were monitored for changes in intensity of discomfort on the VAS.

Vibration Protocol:
MVC, pause, then 60% MVC for 5 seconds
Start two-hour vibration exposure
Sample EMG, force and acceleration signals
(time: 0, 15, 30, 45, 60, 75, 100, 120 (minutes))
Record onset of discomfort and intensity of discomfort via VAS
60% MVC for 5 seconds

The vibration flight protocol consisted of two hours' exposure to each axis of vibration as recorded in the UH-1-H by the U. S. Army Aeromedical Research Lab. At least two weeks were allowed between testing each axis of vibration. The two hours of vibration consisted of four take-offs and landings with each "flight" lasting 30 minutes.

Vibration "Flight" Protocol:

0-1 minutes	Engine running
1-2	Hover
2-4	Hover at 100 knots
4-26	Cruise at 100 knots
26-28	100 knots to hover
28-29	Hover
29-30	Engine running

Results

It was not possible to discern a difference in the EMG data obtained during the vibration tests from noise in the system. Hence these data could not be used as an index of fatigue.

However, there were differences in the EMG center frequency of the EMG signal when comparing the lumbar musculature's pre-test activity to its post-test activity during a 60% maximum voluntary contraction effort (Figures 14 through 16). The only marginally significant ($p < .07$) difference (with respect to initial activity), however, occurred in males (Figure 14) maintaining the static posture typical of the UH-1-H pilot. As can be seen, the percent change in EMG spectrum center frequency was greater than that due to any of the vibration exposures. The only marginally significant ($p < .07$) difference was between the static posture and the up and down vibration in the males (Figure 14).

The subjective discomfort response of all subjects to two-hour exposure to static posture or seated vibration (Figures 17 and 18) was both increasing with time and highly significant. When comparing changes, either within or between sexes (Figures 19 and 20), the only significant differences in the changes were in the males (Figure 19), comparing discomfort due to static posture with discomfort due to up and down vibration ($p < .05$) and side-to-side vibration ($p < .025$). Except when compared with discomfort in females due to fore-aft vibration, the static posture always created more discomfort.

Discussion

In reviewing the objective and subjective variables involved in fatigue and discomfort responses to the sustained static and vibrating UH-1-H specific seating environment, it is apparent that the posture maintained is the more significant factor. It must be kept in mind that the subject/pilot is slumped forward, a posture in which the back is not well supported by the back of the seat. In addition, the UH-1-H vibration frequency is approximately two times greater than the upright seated operator's vertical natural frequency and approximately seven to ten times that of the fore-aft and side-to-side natural frequencies (ISO, 1978). The mismatch of driving to natural frequencies may be another reason for the lack of effect of the vibration.

Onset of discomfort occurred sooner in this study than did onset of pain in the study by Shanahan and Reading (1984). Levels of discomfort for males were comparable to the Shanahan and Reading study in up-and-down and side-to-side vibration. The males in this study exhibited greater discomfort than those in the Shanahan and Reading study in fore-aft vibration and static sitting.

According to Keegan (1953), as one sits, the lumbar curve flattens. Schultz et al. (1982) have shown significant increases in intervertebral disk loads with only slight increases in load held in the hand (an increase of flexion moment). The studies of Schultz et al. (1979) and Tencer and Ahmed (1981) also show that the lumbar motion segment responds differently when its facets have been removed. Thus, if the facet joints open up due to a flexed posture (e.g., sitting down), it is likely that more of the load and stability requirements are shifted to the disk. In her epidemiological work on acute herniated lumbar disks, Kelsey (1975) found an association between sitting and the relative risk of acute herniation of a lumbar disk. Finally, Andersson et al. (1974; 5 studies) have performed extensive work studying the effect of seated posture on the lumbar erector spinae muscle activity and on disc pressure and have shown that a reclined posture (extension) minimizes both.

Conclusions

Helicopter seat and cockpit design would benefit from a more ergonomically oriented design which allows good support for the pilot's back, since posture is more significantly associated with fatigue and discomfort in the UH-1-H environment.

Military Significance. Low back pain in conjunction with vibration exposure is recognized as a health problem in certain environments. The low back pain and discomfort reported by helicopter pilots could, however, be influenced by posture. Knowledge of this interaction is critical to the correct ergonomic design of the cockpit and thus influences the layout of controls. If vibration effects are independent of posture, then the best approach may be to design vibration isolation seats for the helicopter. But, either piece of information is important for future helicopter design. The relationships among posture, vibration and pilot performance are not known, but it is likely that they have important military significance for the pilot population.

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Figures

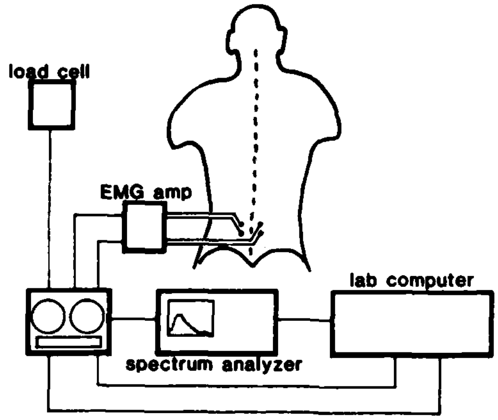


Figure 1. Schematic of the instrumentation set-up used to monitor the center frequency shift of the erector spinae muscle electromyographic activity spectrum due to isometric extension efforts held to exhaustion (fatigue).

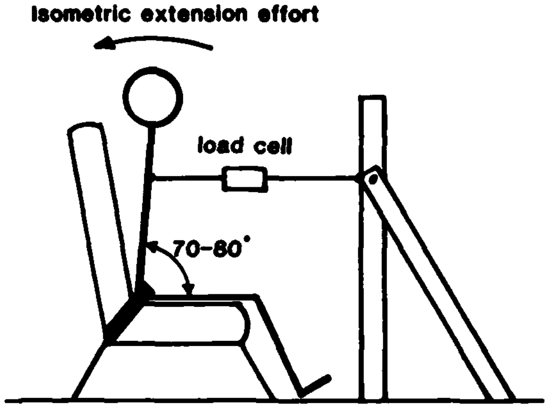
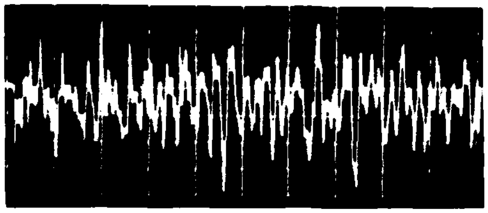
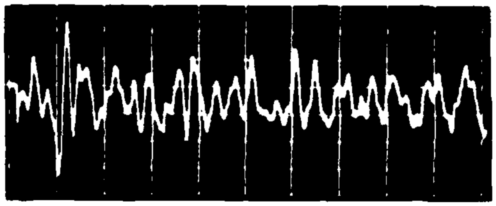


Figure 2. Side view of set-up used to evaluate fatiguing isometric extension efforts on the lumbar musculature.



TIME A: 99.99mSEC/
SPAN: 0.000HZ-200.00HZ SN:1.8+00V
FS:±2.5+00V 6.3-01V/

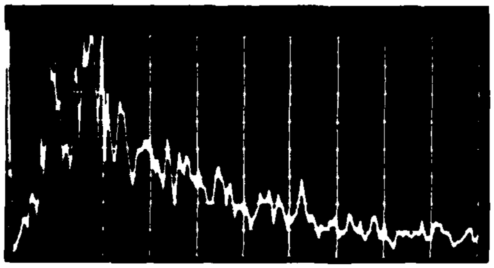
Figure 3. Beginning of effort.



TIME A: 99.99mSEC/
SPAN: 0.000HZ-200.00HZ SN:1.8+00V
FS:±2.5+00V 6.3-01V/

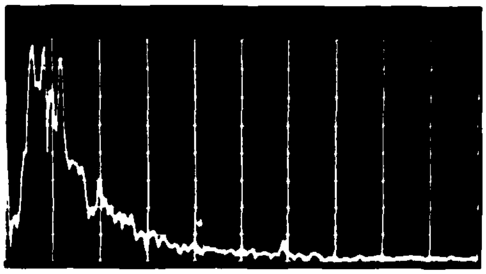
Figure 4. End of effort.

Figures 3 and 4. Typical erector spinae electromyographic data plotted with respect to time. These data show the EMG signal at the beginning and end of a typical lumbar erector spinae isometric extension effort held to exhaustion.



PWR SPECT A :0.23E-02V 0. HZ
N: 40 :1HZ SPAN:0.000HZ-200.00HZ
SN:5.6+00V FS:1.1-01V 1.4-02V/

Figure 5. Beginning of effort.



PWR SPECT A :1.06E-01V 0.HZ
N: 40:1HZ SPAN:0.000HZ-200.00HZ
SN:5.6+00V FS:1.1-01V 1.4-02V/

Figure 6. End of effort.

Figures 5 and 6. The frequency components of typical lumbar erector spinae electromyographic data at the beginning and end of an isometric extension effort. Note the shift toward the lower frequencies (toward the left) of the spectrum taken at the end of the isometric extension effort (Figure 6).

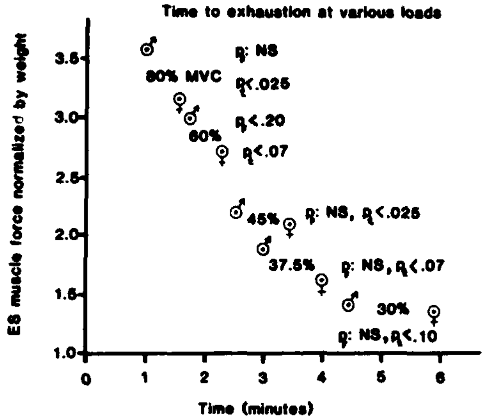


Figure 7. Time duration for which subjects (male and female) were able to maintain various proportions of maximum voluntary contraction extension efforts prior to exhaustion.

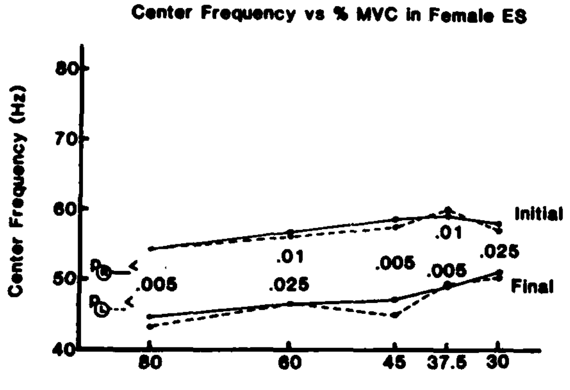


Figure 8. Levels of significance of differences between the initial and final center frequencies of the EMG activities due to various proportions of maximum voluntary contraction fatiguing efforts. There were significant differences at all levels and for both right and left erector spinae muscle groups in the females tested.

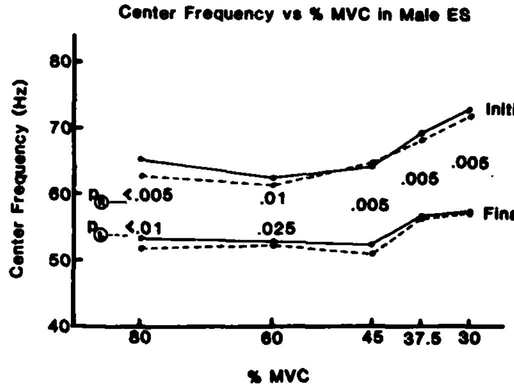


Figure 9. Levels of significance of differences between the initial and final center frequencies of the EMG activities due to various proportions of maximum voluntary contraction fatiguing efforts. There were significant differences at all levels and for both right and left erector spinae muscle groups in the males tested.

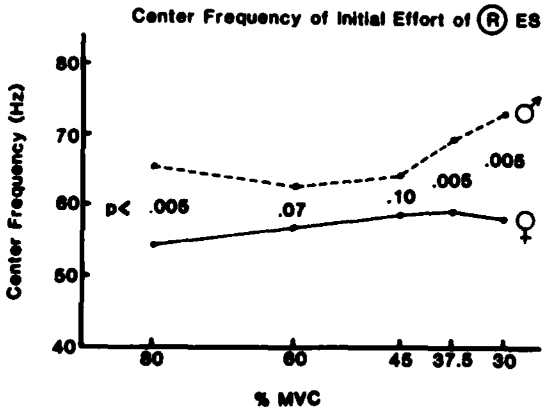


Figure 10. Level of significance of differences in the EMG spectrum center frequencies due to sex for various levels of maximum voluntary contraction isometric fatiguing efforts in the right erector spinae muscle group.

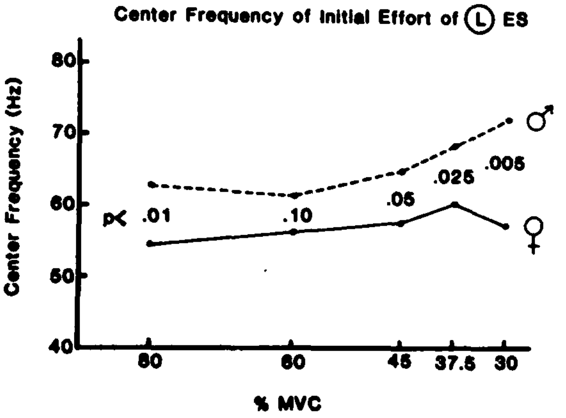


Figure 11. Level of significance of differences in the EMG spectrum center frequencies due to sex for various levels of maximum voluntary contraction isometric fatiguing efforts in the left erector spinae muscle group.

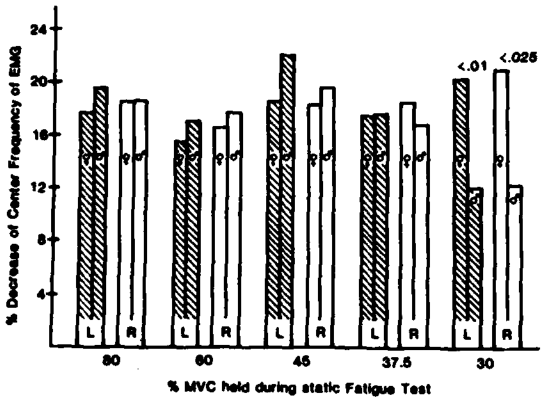


Figure 12. Comparison between sexes of the left and right erector spinae fatigue responses as indicated by the percent decrease in center frequency of the EMG spectrum as a function of proportion of maximum voluntary contraction isometric extension fatigue effort. Only at the 30% MVC level is there a significant difference between sexes.

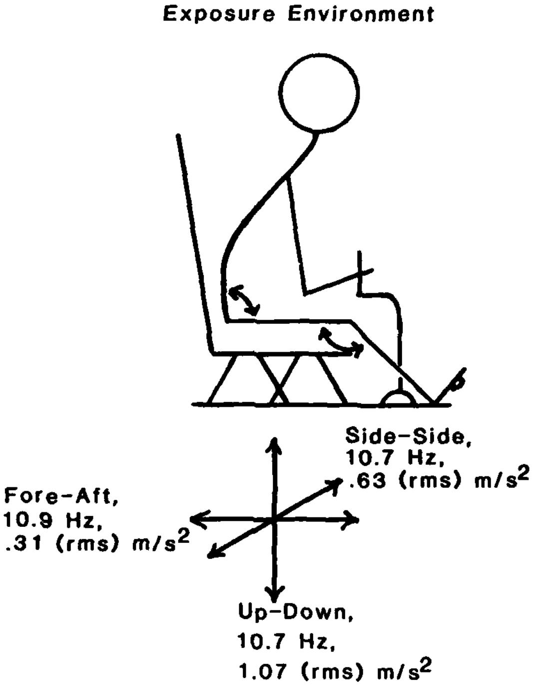


Figure 13. Main acceleration and frequency components of the UH-1-H specific vibration environment for each of three axes.

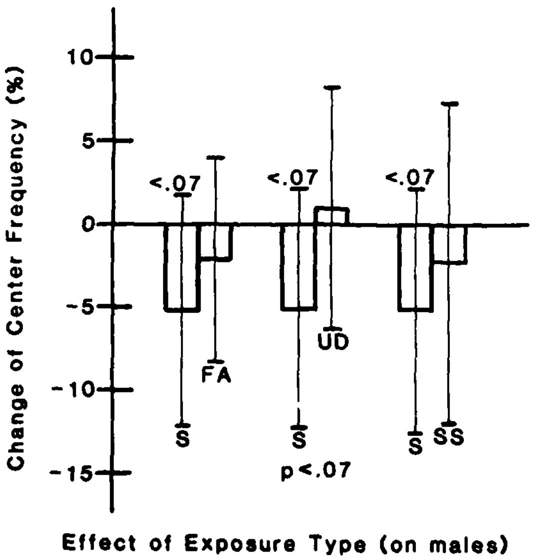


Figure 14. Effect of (S) Static Sitting, (FA) Fore-Aft, (UD) Up-and-Down, and (SS) Side-to-Side vibration exposures on males. There was a marginally significant effect due to static sitting exposure and a marginally significant difference between static sitting and up-and-down vibration exposures. No other exposures or differences were significant.

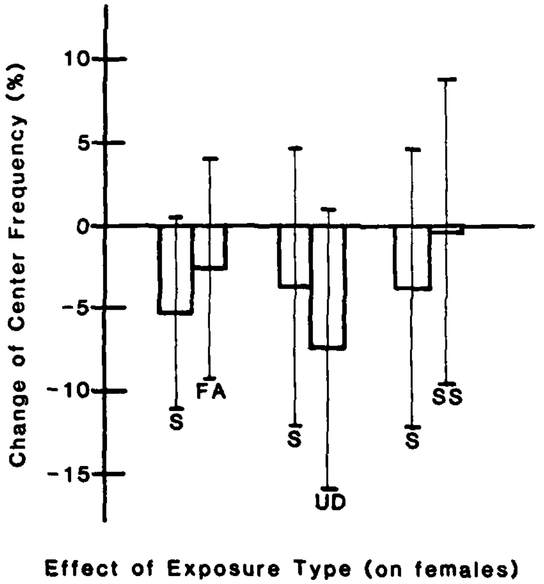


Figure 15. Effect of (S) Static Sitting, (FA) Fore-Aft, (UD) Up-and-Down, and (SS) Side-to-Side vibration exposures on females. There were no significant changes due to any exposure, nor were there any significant differences between static sitting and any vibration exposure.

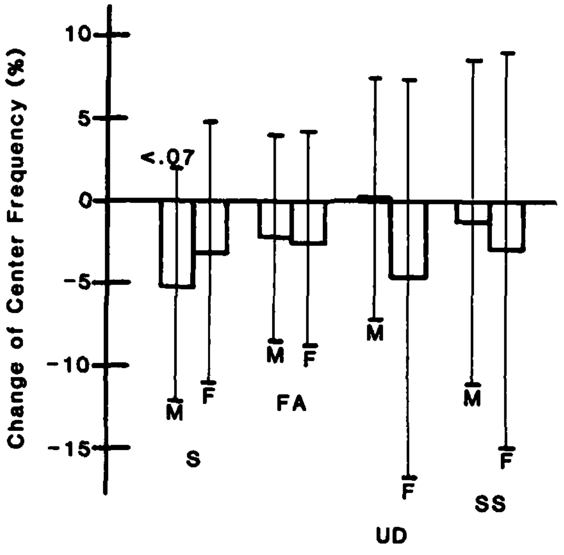


Figure 16. Effect of sex (male vs female) on the response to (S) Static Sitting, (FA) Fore-Aft, (UD) Up-and-Down, and (SS) Side-to-Side vibration exposures. Only males had a marginally significant response to static sitting. There were no significant differences due to sex.

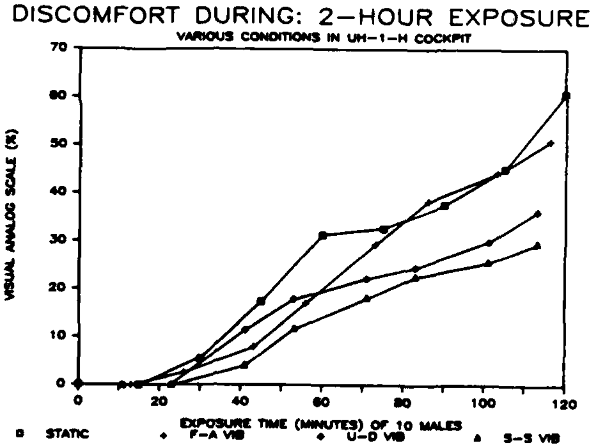


Figure 17. Discomfort increase over time for males exposed to Static Sitting, Fore-Aft, Up-and-Down, and Side-to-Side vibration.

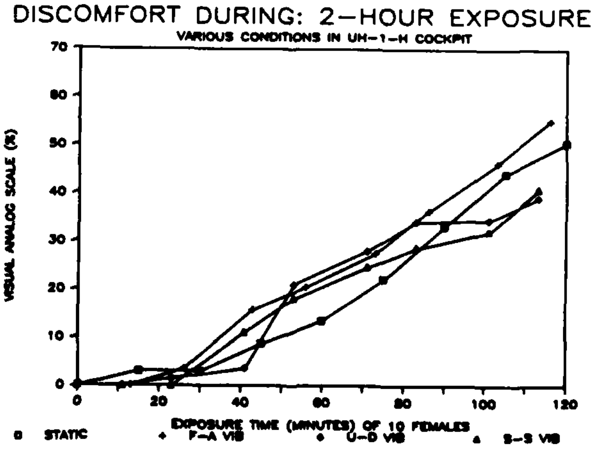


Figure 18. Discomfort increase over time for females exposed to Static Sitting, Fore-Aft, Up-and-Down, and Side-to-Side vibration.

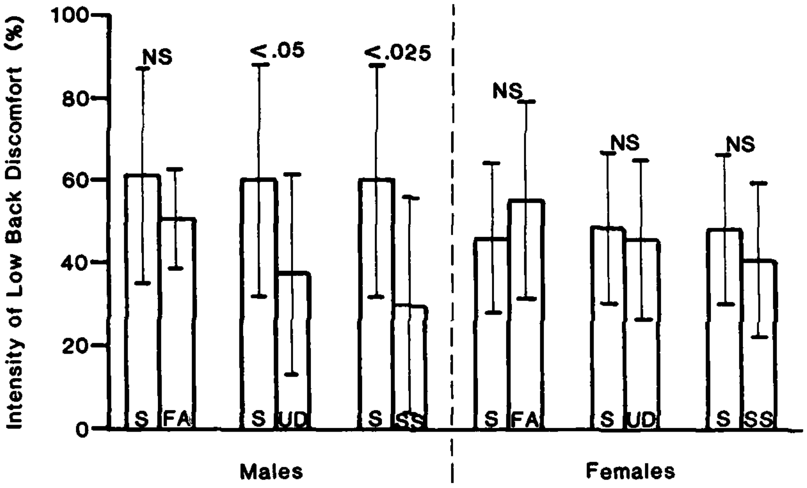


Figure 19. Intensity of low back discomfort during (S) Static sitting, (FA) Fore-Aft, (UD) Up-and-Down, and (SS) Side-to-Side vibration exposures. All final levels of discomfort are significantly different from the initial levels. Only males showed significant differences between discomfort due to static sitting, up-and-down and side-to-side exposures.

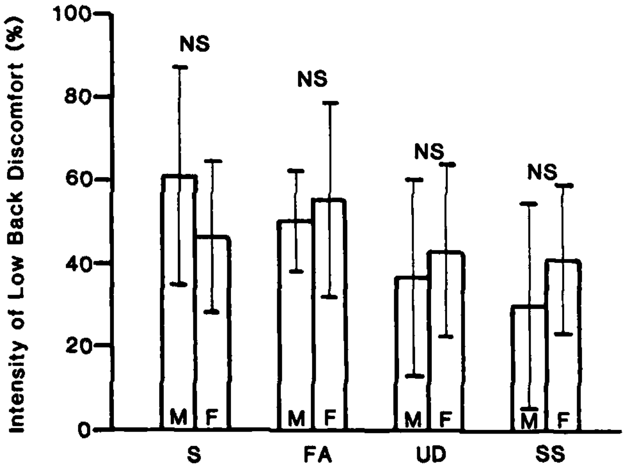


Figure 20. There were no significant differences between sexes at the final levels of discomfort for each exposure type.

DISCUSSION

BOWDEN, CA: Both you and Shanahan and Reading (Aviat. Space Environ. Med. 55: 117-121, 1984) report that an Atari videogame was used as a simulated task. I appreciate the value that toys can have in scientific research; however, as I understand it, the controls of some video games are not proportional controls, but are simply sets of electrical switches, so that fine control may not be required in actually carrying out a task. Can you say whether your particular game was of this type, and could you comment on the role of the control task in backache?

WILDER, US: I cannot comment on the role of the control task in backache; but our game was of this type, and it was necessary to move the stick to a certain limit before creating contact which would then alter the game's response. The main reason for using this game was that it would ensure that the head was pointed forward, looking at something in front of the cockpit; and, also, that there was some task that the hand was performing so that there would be at least some operation of the helicopter cyclic.

TROUP, UK: On the whole, I agree with the deductions and conclusions that you drew from your results. However, there are a number of things about the use of EMGs which I am very doubtful about, in particular, the use of this well-established business of measuring the power spectrum -- the frequency analysis of the EMG. I really think it is something we should question very strongly. If you have a strong interference pattern from the EMG waveforms, it is quite justifiable to treat that as if it were sinusoidal; and it is quite justifiable to use a rectified integrated analysis to look at the total electrical activity. This is then divided, of course, into the various frequency wavebands, and we get this picture. With low levels of activity, such as we find in postural fatigue, or in low levels of postural maintenance, where, I guess, we are talking about 10% or less of the maximal voluntary contraction, you are getting something which is totally unlike a sinusoidal waveform. You are getting a series of discrete pieces of activity. Integration is irrelevant for that, and what matters then is not only the rise time of each individual potential and their frequency, but also the relaxation time; in other words, the twitch tension of the muscle fibre. Shanahan and Reading spoke about muscle spasm. Now muscle spasm; again, this needs to be defined, but, I think, it is typical of muscle spasm that there is a prolongation of twitch tension. In that case, if the back muscles are fatigued, then we get a decrease in the electrical activity measured, but the passive tension remains the same. So, I think, there are a lot of problems which have to be sorted out. I would be happier using wire electrodes because, at least, you can look at the different components of the erector spinae muscles, multifidus, in particular; and, I think, one should look at the raw waveform and analyze it with much greater elegance and precision, rather than using the rather sophisticated method that we have heard about.

WILDER, US: Others have looked at EMG activity and found that the one method which gives the most obvious change was the shift in center frequency. The level of significance was 0.07, so there was still quite a bit of variance in it, and the conclusions as to whether or not that does show significance or trends is still indeterminate. We were not able to monitor the EMG activity during vibration, because the levels were so low. So we only measured the activity during a rather large extension effort. At the time, that was the best we could do.

TROUP, UK: Your answer raises another question in my mind. It's very possible that different populations of muscle fibres are involved in the different activities. Certainly, I would put forward a hypothesis that once postural fatigue has developed, and possibly, when muscle spasm -- whatever we mean by that -- has developed it may be a transition to the slow type of muscle fibre; whereas, in the maximum voluntary contractions I would guess that a different population is involved. The myopotentials from these different fibre types are, again, very different, and, I think, that should be looked at also.

VAN VLIET, CA: I am a little bit concerned with your conclusions on posture, as related to vibration in the helicopter environment. From the point of view of vibration, the helicopter is a very "dirty" vehicle. It has vibrations at all frequencies. The 11-Hz frequency is a blade-pass frequency. For a 2-bladed rotor, that corresponds to a main rotor frequency of just over 5 Hz. I believe that your results would probably be significantly different if you used, perhaps, a more complete vibration spectrum for representing the vibration environment.

WILDER, US: The vibration signal that we used was recorded from the floor of a tuned UH-1H helicopter, and we obtained vibrations from each of three directions. The predominant frequency was 10.8 Hz and there were other components of that signal. The signal was used to drive our vibration-simulation apparatus, which has a major roll-off, I believe, at around 14 Hz. So it was not a pure sinusoidal signal that was imposed on the subject. Rather, it was vibration as found in the field.

VAN VLIET, CA: Did you use a 6 degree-of-freedom simulator? In other words, were you simulating 3 rotations and 3 translations?

WILDER, US: With the limitations of our equipment, we could only look at one axis of vibration at a time, so we could not see the coupling effect.

BOWDEN, CA: I had hoped that the relationship between vibration and posture would be a subject for discussion here. All I will say is that the vibration in helicopters, in part, imposes the posture: and Mr. Wilder's group, I think, told the subjects to assume the posture which helicopter pilots assume, either in a static or vibrating environment. They did not address the question of whether, if a helicopter did not vibrate at all, pilots could assume a different posture and still effectively control it. So, in that sense, vibration is important; what Mr. Wilder has shown is that it perhaps is not the principal direct stress on the pilot.

VAN VLIET, CA: My point is that the environment has not been completely simulated.

LOMBALGIES DES PILOTES D'HELICOPTERES
FACTEURS ETIOPATHOGENIQUES

Par

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RESUME

Les algies vertébrales demeurent encore à l'heure actuelle une des manifestations pathologiques préoccupantes du pilote d'hélicoptère.

La physiopathogénie est liée à deux facteurs : un facteur postural, un facteur vibratoire.

Du point de vue postural, notre but a été d'individualiser et de déterminer les caractéristiques de position du rachis d'un sujet assis au poste de pilotage. A partir des données obtenues sur des radiographies à l'échelle 1 nous avons défini des règles à respecter dans la conception et la réalisation des sièges d'hélicoptères.

En ce qui concerne les vibrations mécaniques, nous avons fait une étude comparative de la transmissibilité des vibrations par différents sièges ou coussins de sièges d'hélicoptères.

Il est possible actuellement d'apporter des améliorations dans le confort du pilotage tant dans le domaine postural que du point de vue protection contre les vibrations.

— $ —

Il y a plus de 40 ans que le pilote d'essais Maurice CLAISSE, après un vol d'endurance sur un hélicoptère Bréguet-Dorand soulignait le caractère désagréable des vibrations se répercutant sur toute la machine : "secoué sur une monture inconfortable pendant une heure de vol, le pilote se hâte d'atterrir, de rentrer au hangar pour soigner ses courbatures".

Malgré les progrès technologiques accomplis depuis le vol du premier gyroplane en 1907, cette remarque rapportée par le vice-amiral JUBELIN reste actuellement valable en grande partie.

La diminution des agressions et des nuisances, l'amélioration de l'ergonomie du poste de pilotage n'ont pas suivi le perfectionnement technique des hélicoptères.

Le nombre important des douleurs vertébrales chez les pilotes d'hélicoptère a été rapporté par de nombreux auteurs dans différents pays. Ainsi en 1957 MISSENARD et GRABER en France notent 50 % de douleurs vertébrales, en 1962 MONTAGARD, SAIS et GUIOT 60 %, SCHULTE-WINTROT et KNOCHE 51 % en RFA, EN 1979 FISCHER ET ZIZELBERGER 67 % et récemment en 1984 SHANAHAN aux U.S.A. note 72.8 % d'épisodes de douleurs vertébrales chez les pilotes.

1 - ASPECTS CLINIQUES

Nous ne ferons que rappeler les quelques données devenues maintenant classiques concernant les lombalgies du pilote d'hélicoptère.

Elles peuvent revêtir deux formes : aigue ou chronique, celles-ci alternant le plus souvent dans le temps chez le même sujet.

La lombalgie chronique est la plus fréquente. Son tableau est celui d'une douleur peu intense à type de fatigue, de pesanteur, de gêne siégeant dans la région lombaire, parfois plus bas située. Elle est transversale médiane, prédominant souvent d'un côté, pouvant irradier vers la région fessière, les crêtes iliaques.

A un degré de plus, cette gêne se transforme en une douleur qui rend le vol très pénible, le pilote cherchant, malgré le maintien constant de la position de ses membres, à changer de posture.

Enfin, dernier stade, cette douleur pénible devient permanente et rend tout mouvement de flexion du tronc très difficile, voire impossible, ceci pendant la période intensive du vol. Il existe assez souvent une contracture musculaire péri-vertébrale avec ou sans inclinaison latérale du tronc.

Les lombalgies aigûes, retrouvées en moyennes dans 50 % des cas, surviennent pour la plupart sur un fond de lombalgie chronique et de façon isolée.

Leur mode de survenue est variable: on relève souvent un début progressif sans effort initial précis mais après un surmenage inhabituel ou une apparition en deux temps, la douleur ne se manifestant que quelques heures après le vol. Parfois le début est brusque mais l'effort ou le faux-mouvement déclenchant sont alors indépendants de la pratique aéronautique.

Ces lombalgies aigües réalisent le tableau du classique tour de rein constitué par une douleur très vive, intense, réveillée au moindre mouvement, limitant tout déplacement.

L'examen, rendu difficile par l'intensité de l'algie, révèle des points douloureux latéro-vertébraux à hauteur des derniers disques, la contracture paravertébrale et surtout l'inflexion antalgique cyphoscoliotique qui se maintient identique dans les divers mouvements rachidiens. Il met en outre en évidence un signe de Lasègue lombaire bilatéral.

Enfin la sciatique, complication majeure de la discopathie dégénérative,a été retrouvée dans quelques cas.

2 - PHYSIOPATHOLOGIE

Les douleurs vertébrales sont une manifestation clinique devenue un peu "le mal du siècle". Il est certain que dans la population générale le pourcentage de cette pathologie vertébrale est loin d'être négligeable. Cependant certaines professions sont plus exposées que d'autres et il est frappant de retrouver chez les conducteurs routiers, en particulier des chauffeurs de poids lourds, une fréquence d'algies vertébrales assez proche de celle des pilotes d'hélicoptères.

Il est donc important de chercher à connaître l'étiologie et la pathogénie de ces manifestations douloureuses.

Il y a quelques années le facteur incriminé en premier lieu était le facteur vibratoire, puis petit à petit la plupart des auteurs ont été amenés à penser qu'un autre facteur important intervenait dans la génèse de cette pathologie vertébrale : c'est le facteur postural.

Aujourd'hui tout le monde s'accorde à penser que ces deux facteurs sont impliqués dans des proportions variables, l'un prenant le pas sur l'autre.

Ainsi on admet aujourd'hui un concept devenu classique : les douleurs vertébrales du pilote d'hélicoptère sont dues à l'action synergique de deux facteurs :

- un facteur postural : la mauvaise position de pilotage
- un facteur mécanique microtraumatique du aux vibrations de l'hélicoptère

2.1. - <u>Le facteur postural</u>

2.1.1 - Données classiques

Bien décrit par SLIOSBERG, le facteur postural est dû à l'utilisation constante et coordonnée des quatre membres dans le pilotage d'hélicoptère.

- les membres inférieurs :

Les pieds reposent sur le palonnier, jambes et cuisses légèrement fléchies. L'appareil ayant tendance à pivoter spontanément sur un côté, la correction effectuée par le rotor anti couple exige en fait une pression dissymétrique permanente au niveau du palonnier.

- les membres supérieurs :

Le membre supérieur droit actionne le manche du pas cyclique situé entre les deux membres inférieurs, le corps étant en flexion presque à angle droit. Sur les appareils actuels le dessin des manches est en général calculé de façon à ce que le coude droit puisse reposer et se caler sur la cuisse droite. Enfin le manche est poussé dans le même sens que la direction de vol, donc presque toujours vers l'avant. Ce fait entraîne une projection de l'épaule droite vers l'avant.

La main gauche actionne le levier de pas collectif en demi flexion, sans exercer d'efforts, la position du levier se calant grâce aux servo-commandes. Cette position néanmoins constante se caractérise par l'inclinaison et l'effacement de l'épaule gauche vers le bas.

- Rachis :

Théoriquement le rachis dorsal et lombaire devrait être solidaire du dossier du siège par un sanglage type harnais. En pratique la nécessité de pilotage à vue constante oblige le pilote à ne pas serrer les bretelles de suspension sur lesquelles, d'ailleurs, il se cale, penché en avant. Le dos s'écarte ainsi du dossier, le rachis cervical se trouve en hyperextension.

2.1.2. - Etude radiographique du rachis

Des études effectuées en 1966 par R.P. DELAHAYE et J. SHICKLE ont montré certaines modifications vertébrales crées par la position du pilotage d'hélicoptère. Les résultats enregistrés, tout en confirmant les angles de confort de WISNER, soulignent les déviations vertébrales rencontrées en position assise. Nous avons voulu compléter ces données et nous avons entrepris grâce à des techniques radiologiques nouvelles une étude complémentaire destinée à mesurer les différents paramètres vertébraux pouvant influer sur le confort du pilote.

Cette notion de confort est complexe. Elle fait intervenir :

- une répartition correcte des pressions unitaires

- un fonctionnement satisfaisant des différents segments corporels lors des phases statiques et dynamiques du vol

- l'inclinaison du dossier du siège

- l'utilisation d'un coussin lombaire réglable

- la nature de l'interface peau-siège

De plus il est bien connu que lorsque l'homme passe de la station debout à la position assise l'ensemble lombaire a tendance à s'effacer et la cyphose dorsale physiologique est moins importante. J.J. KEEGAN insiste sur le rôle important des muscles postérieurs de la cuisse et des muscles fessiers dans l'effacement de la courbure lombaire en position assise. Mais si les cuisses sont fléchies sur le tronc il se produit une rotation du bassin et la lordose disparait entièrement.

L'étude entreprise par le Laboratoire de Médecine Aérospatiale du Centre d'Essais en Vol en collaboration avec le service de Radiologie de l'Hopital d'Instruction des Armées BEGIN a donc eu pour but d'individualiser et de déterminer les caractéristiques de position du rachis d'un *sujet assis en position de pilotage et créant les meilleures sensations de* confort.

2.1.2.1. - Les différentes opérations de cette expérimentation.

Elles nécessitent la mise en oeuvre de plusieurs réalisations :

- construction d'un bâti mécanique permettant l'adaptation de tous les sièges. Ce bâti permet une représentation de cabine à l'échelle 1 avec mise en place du manche, du palonnier, de la planche de bord et du dispositif positionnant l'oeil. Le siège servant de référence, les différents équipements sont disposés conformément à l'appareil à simuler.

- construction d'un chassis radiologique. Ce dispositif original permet la réalisation de radiographies en conservant pour chaque type d'expérimentation les mêmes caractéristiques géométriques. Il facilite la reproductibilité et, par là, la comparaison des différentes déterminations chiffrées mesurées sur les radiographies. Ce chassis radiologique vertical doit maintenir *verticalement* derrière le pilote assis sur le siège étudié, 3 grilles 30 X 120 cm, 3 cassettes 30 X 120 cm, 3 plaques en plastique quadrillé 5 X 5 permettant les mensurations sur les radiographies. Ce dispositif est mobile pour permettre l'orientation des cassettes dans le plan vertical, indépendamment l'une de l'autre. Chaque cassette est également orientable en rotation autour de son axe vertical pour qu'elle soit perpendiculaire aux Rayons X. Le porte cassettes mobile est placé à 3.50 m du tube radiogène. Le pilote assis sur le siège est placé le plus près possible du porte cassettes. La colonne vertébrale doit se trouver au centre d'une des cassettes latérales.

2.1.2.2. Définition des différentes mesures effectuées sur les radiographies

L'étude des radiographies de la colonne oblige à définir 16 valeurs, angles ou distances entre les points remarquables.

Leur répartition est la suivante :

1 - Angle de la cheville : angle pied-jambe
2 - Angle du genou : angle fémur-tibia
3 - Angle du coude : angle bras-avant-bras
4 - Angle de l'épaule : angle du bras avec la verticale mesurant l'élévation antérieure du bras
5 - Angle du rachis cervical : angle entre la ligne joignant l'angle postéro supérieur de l'odontoïde à l'angle postéro inférieur de C_7 et la verticale
6 - Angle de cyphose dorsale : angle formé par la perpendiculaire au plateau supérieur de D_4 et celle au plateau inférieur de D_{12}
7 - Lordose lombaire ou corde lombaire : droite joignant l'angle postéro supérieur de L_1 à l'angle postéro supérieur de S_1. Elle se mesure en mm. Elle est positive pour une lordose et négative pour une cyphose.
8 - Lordose définie par Rabischong : angle formé par les perpendiculaires au plateau supérieur de D_{12} et inférieur de L_5. L'angle est négatif en cas de cyphose.
9 - Angle corde lombaire-verticale
10 - Angle corde cervico-sacrée ou corde vertébrale-verticale : angle formé par la droite allant de la jonction cervico-dorsale à l'angle antéro-supérieur de S_1 et la verticale. Cet angle est très important car il donne une indication *sur la courbure de la colonne et l'inclinaison du tronc vers l'avant.*
11 - Angle fémur-corde cervico-sacrée : angle formé par l'axe du fémur et la droite allant de la jonction cervico-dorsale (angle postéro supérieur de D_1) à l'angle antéro-supérieur de S_1.
12 - Angle fémur-corde lombaire : angle formé par l'axe du fémur et le prolongement de la corde lombaire. Cet angle nous apparait très important parce qu'il a un rapport avec le sacrum mal visualisé sur les radiographies à cause des armatures métalliques du siège. La position de la colonne lombaire par rapport au fémur est en partie définie par cet angle.
13 - Angle fémur-dossier : angle formé par l'axe du fémur et le dossier du siège

15 - Angle corde vertébrale-rachis cervical : angle formé par la droite allant de la jonction cervico-dorsale à l'angle supérieur de S_1 et le rachis cervical.

16 - Angle d'inclinaison fémorale : angle formé par l'axe du fémur avec l'horizontale.

17 - Distance d'assise fémorale : distance face antérieure du coussin du siège et corde lombaire. Cette mesure s'est révélée difficile à déterminer avec précision sur les radiographies car les coussins de siège ne sont pas suffisamment opaques.

2.1.2.3. - Résultats

Nous avons pris pour référence des angles préconisés par REBIFFE,ZAYANA et TARRIERE, définis comme angles de confort.

Il ressort de cette étude que la position de la colonne vertébrale est rarement satisfaisante dans son ensemble. Au niveau de la colonne lombaire on note de manière assez homogène une rectitude avec une tendance à la cyphose.

- Alouette III : La position de l'ensemble de la colonne n'est pas satisfaisante puisque l'ensemble thorax-bassin est très incliné vers l'avant au delà de la verticale. Cette position de la colonne entraîne bien évidemment une rectitude de la colonne lombaire avec augmentation de la cyphose dorsale et surtout une colonne cervicale en hyperextension lors du pilotage à vue.

Cette attitude cyphotique est due essentiellement à la mauvaise position du manche.

- Gazelle : Lorsque l'on regarde la silhouette d'ensemble de la colonne, on peut penser que la position assise est correcte puisque le dos semble aligné sur le dossier.

En fait, les radiographies montrent encore une fois une rectitude lombaire avec bascule du bassin et fermeture de l'angle fémur-colonne lombaire. Et lorsque l'on regarde le positionnement du siège dans la cabine, on s'aperçoit que ce siège est très bas sur le plancher. Ainsi pour éviter de travailler avec le membre inférieur presqu'en extension, le pilote rapproche le siège du palonnier, ce qui entraîne une fermeture de l'angle du genou proche de l'angle de confort, mais aussi un relèvement du fémur d'où une bascule du bassin et une rectitude lombaire. De plus cette position fait que le pilote a une assise ischiatique et non plus fémorale.

- Puma : La position est dans l'ensemble satisfaisante. Il faut noter cependant une tendance au pilotage bras tendu sans appui ce qui risque d'entraîner une certaine fatigue de la part du pilote.

2.2. - Facteur mécanique : les vibrations

Résultat du rendement imparfait de tout système mécanique en mouvement, les vibrations représentent une forme dégradée d'énergie que l'opérateur humain récupère directement à son poste de travail sous forme de nuisances.

Le domaine aéronautique est loin d'être épargné par les agressions vibratoires et en particulier l'hélicoptère qui engendre assez souvent des vibrations de haut niveau

Ces vibrations enregistrées à bord des hélicoptères sont de deux origines : mécaniques d'une part et aérodynamiques d'autre part.

- Les vibrations d'origine mécanique :

. De basse fréquence . elles sont provoquées par le rotor principal tournant à la fréquence et par les N pales de ce rotor. Les causes sont multiples. Nous retiendrons parmi les principales :

- le fonctionnement des dispositifs articulés liés à la technologie même de l'appareil, ils engendrent des fréquences N principalement sur l'axe Z
- la différence de trainée des pales avançantes et reculantes.

. De moyenne et haute fréquence, elle ont pour origine :

- le fonctionnement des moteurs ou turbines
- le rotor de fréquence et N pales (fréquence N)
- les organes mobiles de transmission.

- Les vibrations d'origine aérodynamique :

De très basse fréquence, elles sont dues aux réponses de la cellule aux excitations aérodynamiques et aux actions du pilote à travers les servo commandes.

Les effets physiologiques des vibrations sont dus aux déformations et aux déplacements relatifs importants que subissent les organes ou les tissus à certaines fréquences.

Le rôle joué par le siège assurant la transmission au pilote des mouvements de l'appareil est donc très important.

2.2.1 - Transmissibilité des vibrations au pilote

Il nous a donc paru utile d'étudier la transmissibilité des vibrations à travers différents sièges ou coussins de siège :

- pour divers types de siège d'hélicoptères : Gazelle
  Dauphin
  Puma équipé du siège Armée de l'Air

- pour un type de siège (Puma SA 330) équipé de coussins de mousse de densité croissante définie ainsi 6A 26A. 35A. 40D. 50D.

L'étude a été effectuée sur plateau vibrant. à accélération constante.

Les paramètres obtenus ont été : accélération au niveau du bassin. accélération au niveau du thorax. accélération au niveau de la tête.

A partir de ces données. il a été possible d'établir des rapports d'accélération : bassin/référence plateau. thorax/référence. tête/référence.

Ici seul nous intéresse le rapport bassin/référence qui donne la transmissibilité des vibrations à travers les différents sièges ou coussins.

Le rapport R est égal à un lorsque la vibration est intégralement transmise entre le plateau et le bassin. Il n'y a donc ni amortissement. ni résonance.

Le rapport est égal à ½ lorsqu'il y a un amortissement qui réduit de moitié le niveau d'accélération du plateau. et égal à 1/4 lorsque cet amortissement divise par 4 le niveau d'accélération du plateau.

Sur les tableaux qui suivent les fréquences de vibrations sont données pour :

- une transmissibilité sans amortissement ni résonance (R = 1)
- *une transmissibilité permettant un amortissement de* 2 (R = ½)
- une transmissibilité permettant un amortissement de 4 (R = 1/4)

2.2.1.1. - Mesure pour divers types de sièges

R	Gazelle	Dauphin	Puma (Armée de l'Air)
1	5 Hz	5 Hz	6 Hz
1/2 trans.			15 Hz
1/4 trans.			

Ces résultats montrent nettement que les trois sièges de la Gazelle. du Dauphin et du Puma équipé du siège d'origine ont pratiquement le même comportement sous vibrations et une transmissibilité identique.

Il faut noter cependant que l'amortissement de 4 n'est jamais atteint. ni celui de 2 pour la Gazelle et le Dauphin . bien que l'on en soit très près à 15 Hz. R est égal à 0.55.

2.2.1.2. - Mesures faites avec le siège du Puma équipé de mousses de densités différentes

R	6A	26A	35A	40C	50D
1	5 Hz	6 Hz	5 Hz	5 Hz	5 Hz
1/2 trans.	12 Hz	15 Hz	11 Hz	8 Hz	9 Hz
1/4 trans.				14 Hz	15 Hz

Ces résultats montrent combien l'augmentation de densité de la mousse équipant le siège favorise un amortissement des vibrations. En effet un amortissement de 2 apparait à des fréquences de 12 et 15 Hz pour des coussins de densité faible et à 8 et 9 Hz pour des coussins de densité supérieure.

Ainsi il apparait que la qualité filtrante d'un siège peut être améliorée très simplement en modifiant la densité de la mousse équipant ce siège.

Il est important de connaître la valeur de l'accélération et de la fréquence de vibration mesurée au niveau du bassin du pilote. C'est elle qui va être responsable des microtraumatismes au niveau de la colonne.

Il faut aussi insister sur l'importance des déphasages que peuvent présenter entre elles les différentes masses corporelles et qui seraient particulièrement nocifs pour le rachis en particulier les changements de phase thorax-bassin. Outre les mouvements axiaux les vibrations d'axe Z produisent sur la colonne vertébrale des oscillations d'avant en arrière : entre 12 et 14 Hz par exemple la colonne dorsale fléchit en avant. Ce phénomène est encore plus net au niveau de la tête qui répond aux oscillations verticales par des oscillations horizontales.

On conçoit que ce mouvement d'avant en arrière. aggravé par la position en hyperextension et par le port du casque qui ajoute une certaine inertie au système puisse engendrer des lésions au niveau de la zone charnière représentée par la colonne cervicale basse.

En fait le mécanisme d'action des vibrations sur la colonne est encore assez mal connu. Le pilote soumis à des vibrations va présenter une contracture musculaire essentiellement paravertébrale, bien souvent réflexe, qui aura tendance à s'opposer au phénomène vibratoire. Cependant cette contraction musculaire ne peut être permanente et très vite une fatigue va apparaître. L'amortisseur musculaire est alors forcé et le surmenage du système disco-ligamentaire va se traduire par l'apparition d'une discopathie dégénérative à l'origine du tableau clinique. Cette action des vibrations va encore être accentuée sur un rachis sensibilisé par une mauvaise posture.

3 - PROTECTION DU PILOTE

Comme dans toute pathologie à caractère professionnel deux objectifs simultanés sont à poursuivre : adapter l'homme à son travail et la machine à son opérateur humain.

3.1. - Protection contre les vibrations

En ce qui concerne les hélicoptères, des progrès considérables peuvent être constatés au plan du niveau vibratoire dans les appareils de la nouvelle génération. Ce fait a été mesuré sur Gazelle ainsi que sur Dauphin ou Ecureuil. Il est dû au perfectionnement technologique qui permet de remplacer les systèmes métalliques articulés par des pièces monobloc en matériau plastique, à l'installation d'amortisseurs diminuant les vibrations engendrées par les rotors et les transmissions en mouvement.

Un autre système de protection est apporté par le siège lui même. Comme nous venons de le voir il est possible d'atténuer considérablement le phénomène vibratoire au niveau du bassin du pilote par l'étude de sièges ayant une qualité de mousse filtrant suffisamment les vibrations. Il est certain que l'amortissement des vibrations au dessous de 5 Hz est très difficile. Cependant si on peut diminuer par 4 le niveau vibratoire mesuré au bassin du pilote et ce à partir de 8 ou 10 Hz alors on aura fait un grand pas vers un nouveau confort dans le pilotage des hélicoptères.

Il reste malheureusement le problème des vibrations selon l'axe X ou Y dont il est très difficile de se protéger si ce n'est par l'adoption de bourrelets latéraux au niveau du siège.

3.2. - Protection par amélioration du siège

Nous avons vu l'importance d'une bonne position de pilotage. La position assise n'est pas une position physiologique. Il est donc important de tout mettre en oeuvre pour respecter le plus possible les courbures vertébrales. Ainsi le pilote doit "se sentir bien" en position assise mais aussi avoir une colonne en bonne position. Le siège doit donc permettre une bonne statique vertébrale.

La sensation de confort dépend :

- de l'angulation segmentaire des membres et du tronc

- de la pression unitaire exercée sur le revêtement cutané. La position assise nécessite un appui ischiatique et fémoral, sur une surface suffisamment souple pour favoriser une absence de point dur. Au niveau du dos, l'appui se réalise avec une inclinaison suffisante du siège. Le dossier du siège et son revêtement doivent permettre de supprimer dans la mesure du possible les points de concentration des contraintes créés par l'appui des formations squelettiques.

En somme, l'appui en position assise doit se faire sur le siège par la plus grande surface des fémurs et du dos.

A partir de l'étude radiographique réalisée sur la position du pilotage pour différents types d'hélicoptères, nous avons déduit quelques caractéristiques souhaitables d'un bon siège d'hélicoptère :

- réglage du siège en déplacement vertical et horizontal
- dossier remontant assez haut avec changement de courbure à hauteur du dos et à inclinaison réglable
- coussin d'appui lombaire réglable
- assise suffisamment profonde permettant un appui correct des fémurs
- bourrelets latéraux sur l'assise et le dossier apportant un meilleur maintien latéral
- accoudoirs réglables.

Il parait souhaitable d'étudier les prototypes plutôt que de déplorer les insuffisances des sièges de série. En effet, l'amélioration de la forme des sièges tendant à se rapprocher des normes de confort bien connues et compatible avec la mission permet d'épargner la musculature du pilote qui reste ainsi plus longtemps disponible pour jouer son rôle d'amortisseur.

A partir de ces données à la fois posturales et vibratoires il est possible de concevoir des sièges qui permettent d'assurer le pilotage des hélicoptères dans un confort satisfaisant. C'est le cas du siège de l'AS 332 version civile fabriqué par la SOCEA en France et qui répond assez bien aux normes de confort.

CONCLUSION

Prononcer les mots de rachis et d'hélicoptère amène à penser algies vertébrales. La sécurité des vols impose de lutter contre elles par l'amélioration du confort du pilote.

Il est certain que des progrès restent à faire. En effet si le délai d'apparition des lombalgies est passé de 300-500 heures de vol il y a quelques années à 1 000-1 500 heures de vol aujourd'hui, il n'en reste pas moins vrai que ces douleurs vertébrales existent toujours.

Or des améliorations sont possibles à la fois au niveau vibratoire et postural.

Un fait est certain, nous connaissons très mal le mécanisme physiopathogénique intime de ces manifestations vertébrales et donc de nombreuses études restent à faire.

En attendant il faut souhaiter que parallèlement à la diminution du niveau vibratoire et à l'amélioration du confort des sièges, une étude plus globale du poste de travail, c'est à dire du poste de pilotage dans son ensemble soit conduite.

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VIBRATION MEASUREMENTS ON HELICOPTER AIRCREW: A NEW APPROACH

by

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SUMMARY

In this paper a new method is proposed for obtaining the time-dependent pattern of vibrations transmitted to the seated pilot, by means of a map showing the direction and magnitude of all measured vectors. The pattern easily allows the observer to distinguish between rotational and translational motion. Because the direction of translational motion (or the axis of rotational motion) is not the same in different flight conditions, a suitable reorientation of the frame of reference is required in order to compare the various situations. In this way it is also possible to observe changes of the spin axis or of the direction line, in case of rotational or translational motion respectively. Some results obtained from measurements on board a helicopter at two sites (seat and backrest) are presented. Three orthogonal acceleration vectors are examined. Patterns corresponding to different flight conditions are shown, before and after frame reorientation. The paper closes with a frequency analysis of some of the measurements, comparing amplitudes and phases of the spectral components at the same frequencies, before and after frame reorientation.

STATEMENT OF THE PROBLEM

Over the past few decades a great deal has been learned about the pathological effects of vibration on the human body. Vibration has been shown to affect the musculoskeletal system and particularly the supporting structures of the trunk. Furthermore many clinical studies have indicated a clear relationship between helicopter vibration and low back pain (3).

An overview of the literature shows different approaches to the general problem of determining how vibration is involved in causing backache. Subjective and objective methods have been used; methods based on a physiological point of view have been widely considered too. Starting from simple situations (12, 18 19, 22) and going through different levels of complexity (5, 7, 8, 21, 24, 27) these studies come to well-known conclusions about discomfort and performance decrements in the situations taken into consideration (1, 2, 4, 6, 10, 11, 16). Few studies are concerned with the biomechanical behaviour of the trunk in a vibrating system environment, mostly because of the complexity of the problem. It is quite difficult to determine "in vivo" how the soft tissues, bones and organs behave under vibrational stresses. Simulation by means of models has been adopted as a method of study, as well (14, 17, 23, 25, 28).

Usually vibration studies analyses are carried out by measuring the vibration transmitted from the aircraft to the seated pilot (20). These measurements are made at particular representative sites such as the seat and the backrest. The most common way of representing the time dependence of the vibration vector w.r has been done by representing separately the time dependence of its three projections along the three orthogonal axes x, y and z of a suitable frame of reference T. In this way the analysis of vibration phenomena is carried out separately for the three axes in the time domain and also in the frequency domain after Fourier transformation.

This approach does not seem adequate to the Authors for the evaluation of vibration affecting the pilot's trunk. The principal limitation of this approach is that a complete picture of the vibration is not expressed; it is analogous to the problem of communicating the three-dimensional shape of the object through a technical drawing which includes only the three orthogonal projections. On this basis it seems to be necessary for the medical investigator to possess a "picture" of the dynamical situation as it evolves in a three-dimensional space. This "picture" becomes a useful pattern for comparison between situations. The aim of the present work was to study a new, reliable, and easy tool for the evaluation of the intensity and direction of vibration. The new method is particularly useful to provide medical investigators with a better understanding of the aetiology and pathogenesis of backache. Many characteristics of the vibrational stresses applied to Sikorsky HH3F pilots of I.A.F. have been studied in this way.

VIBRATION PATTERNS

In practical conditions vibration measurements are made indirectly by means of measurement of the resultant acceleration vectors. Thus three accelerations measured along x, y, and x axes. Experimental conditions are as described in Fig. 1, which shows the two measuring sites on the seat and the backrest. The seat site lies under the buttocks, in proximity to the ischial tuberosities and the backrest site is near the lumbar region. Triaxial accelerometers enclosed in a flexible flat rubber disc have been adopted; the discs are mounted on the seat and on the backrest. This system allows one to measure at a given time the three orthogonal projections of any vibration vector v/r. The orientation of the frame T of the two accelerometers is according to ISO 2631 (15).

In order to obtain the pattern for the dynamical situation, it is possible to make the transformation from Cartesian coordinates x, y and z into polar coordinates ϕ, θ and ρ, and to consider the intersection of the vector r with the Gaussian unit sphere at a point P having coordinates ϕ and θ. Then the unit sphere is mapped onto a plane using a Flamsteed projection. The information about the magnitude ρ can be given now by associating with the image of point P on the Flamsteed projection a polygon of radius proportional to the magnitude ρ of r. By repeating this procedure for all measured vibration vectors, we obtain a pattern which gives us information about the numbers of points P together with the corresponding vector magnitudes on any area of the Flamsteed projection.

Analysis has been carried out separately for the seat and the backrest, using sequences of 2048 measurements taken with a sampling time of 2.5 ms. The length of each measurement is then 5.12 s. Some patterns are shown in Fig. 2 (seat) and in Fig. 3 (backrest); the measurements have been made in different flight conditions. Two basic patterns are present: i) rotational motion (rotational motion is that in which the acceleration vector moves in a circle in space); ii) translational motion (translational motion is where the acceleration vector executes a sinusoidal change in magnitude while remaining in the same direction in space). In some cases the combination of both these patterns is present. We observed that in most cases the patterns of rotational motion are not orientated according to one of the three coordinate planes. Furthermore the patterns of translational motion mostly are not orientated according to one of the three coordinate axes. Because of this, comparison of similar or different situations is very difficult.

In order to assist the medical investigator in the analysis and to compare similar or different situations, reorientation of the frame of reference T into a new one has been adopted. The aim is to orient the pattern of every translational motion along the z axis, and the pattern of every rotational motion to the y-z plane. The results so obtained are shown further in this paper. In order to achieve the reorientation the following algorithm has been adopted. The algorithm is explained with reference to Cartesian coordinates, but it is obviously still valid for the polar coordinates used in the Flamsteed projection.

We shall add all the vectors r that have positive z-components, so obtaining the vector r; similarly we shall add all the vectors r that have negative z-components, so obtaining the vector r_n. We consider next the plane α defined by the two vectors r_p and r_n (provided the angle between these vectors (λ) is different from π) and on this plane we drop the perpendicular line r_a to the bisector of the angle λ (see Fig. 4). Then we can rotate the coordinate system associated with the whole of vectors r around the z axis and the y axis in order to superimpose the r_a line on the z axis. Because, after the rotation the vectors r generating r_p and r_n change, this procedure may need some iterations. If the prevailing motion in the pattern under consideration is translational, the reorientation procedure is complete.

On the other hand, if the prevailing motion is rotational, the axes could now be re-oriented by rotation around the z-axis until the prevailing rotational motion is in the y-z plane.

This procedure has been applied to four vibration measurements, of which two were of translational motion and two were of rotational motion. Results are shown in Figure 5. In order to show the orientation of the original frame of reference T after all the rotations have been carried out, the polar co-ordinate grid corresponding to T has been drawn in both the original and re-oriented projections. The spherical triangle defined by the positive x, y and z axes is indicated by shading. The values of the roll, pitch and yaw angles corresponding to the transformation are indicated with each graph. The graphs demonstrate that the prevailing vibratory motion, which is obviously the rotational motion caused by the main rotor of the helicopter, is transformed into translational motion in some flight situations.

Furthermore, the axis of rotational motion is not fixed in space, but has its own motion, and may have different directions at the seat pan and backrest. The motion of the axis of rotation is shown clearly by partitioning a set of 2048 measurements (samples) into segments. The result of this partition is shown in Figure 6: the 2048 measurements (samples) from measurement No. 9 have been partitioned into 16 segments of different length. The variation in the direction of the axis of rotation from segment to segment is evident.

Griffin and Whitham (8) have shown that, from the point of view of subjective discomfort, it is not possible to distinguish between the case in which vibrations along two orthogonal axes are in phase (with a consequent translational motion) and the case in which the phase of the vibrations differ by 90° (with a consequent rotational motion). This happens at low frequencies, as well.

Nevertheless, the physiological effects of these two different situations cannot be considered identical, neither in the short term (backache etc.) nor in the long term (arthrosis etc.) (26). Furthermore from a physiological point of view rotational motion around an axis forward inclined cannot be regarded as identical to a rotational motion around an axis inclined in a different way, e.g. laterally inclined. Eventually if the axis of the rotational motion varies from site to site, (e.g. seat to backrest) the trunk is subject to torsional stresses, as well. These observations point out the benefits of the proposed method to medical investigators.

FREQUENCY ANALYSIS

Frequency analysis of the vibration present on board a helicopter show the following well known results (3, 9, 13): spectral components around the main rotor revolution frequency f and around Nf (being N the number of rotor blades) are present, with related harmonics. Analogous phenomena are induced by the tail rotor but, due to its smaller dimensions, the effects on the cabin are relevant. Low frequency spectral components probably related to aerodynamic phenomena can be detected too. Some other different spectral components can be detected, but investigation of their possible origin should be carried out on a case by case basis.

It is interesting to compare the frequency analysis of the finite discrete time-series which are related with the three projections x, y and z of vector r, with the frequency analysis of the finite discrete time-series which are related with the three projections x', y' and z' of r along the coordinate axes of the frame of reference after the reorientation. Figs. 7, 8, 9 and 10 show frequency analysis results of some measured acceleration signals before (left) and after (right) reorientation. For each axis, amplitude representation is at the top, phase representation is at the bottom. Amplitude and phase value of the FFT spectral analysis are shown only if the amplitude is greater than 5% of the overall maximum value. Phase is still shown because in the case of rotational motion it is of interest to compare the phases of spectral components on the various axes.

Fig. 7 shows the analysis of measurement No.2, made at the seat site just after the takeoff. The blade frequency, around 18 Hz (corresponding to 5f, being here N=5) is almost the only one. With respect to reference frame T, the maximum value of the blade frequency is along z axis, and the ratio between the amplitude at the blade frequency along x axis and the amplitude along z axis is 0.37; between the amplitude along the y axis and the value along the z axis this ratio is 0.46. After reorientation these two ratios drop to 0.13 and 0.14 respectively, showing the reorientation has substantially identified the direction along which the main power of the vibration is oriented. This direction is obviously the direction of the z axis after the reorientation. It is interesting to point out that spectral components with frequencies less than the blade frequency belong to x-z plane, and those with frequencies greater than the blade frequency belong to x-y plane.

Fig. 8 shows the analysis of measurement No. 20, made at the seat site in translational flight conditions. Rotational motion due to spectral components along y and z axes (with a phase lag of about 90° and with an amplitude ratio equal to 0.6) is clearly shown by reorientation.

Fig. 9 shows the analysis of measurement No. 9, made at the seat site in hovering conditions, with ground effect. Superior harmonics of the blade frequency have considerable greater amplitudes than in the previous cases. Rotational motion is mainly at the blade frequency and to its third harmonic. Spectral components are still present along the x axis after reorientation. Discomfort is considerably greater in this situation than in the previous as well.

As far as measurements at the backrest site are concerned, the results of frequency analysis is substantially similar. Fig. 10 shows just the analysis of measurement No. 21, in translational flight.

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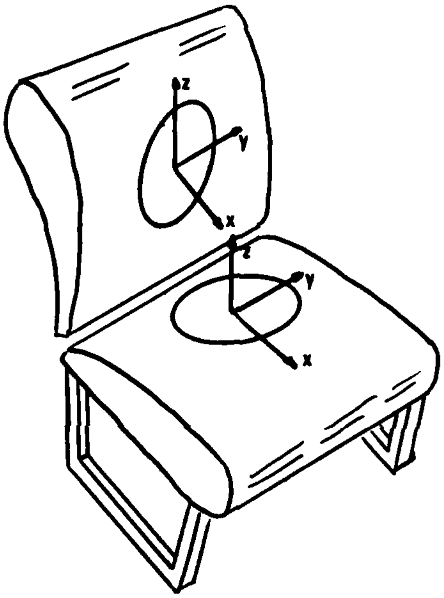


Fig. 1- Position on the seat and backrest of the two thriaxial accelerometers

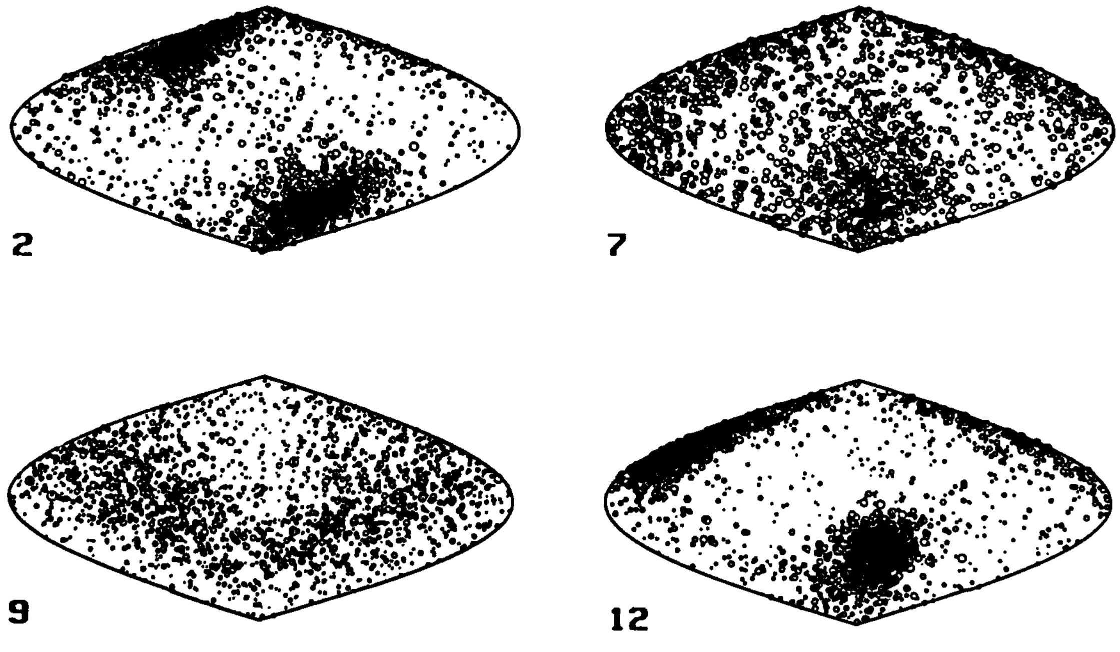


Fig. 2- Pattern of the addition of the three acceleration vectors measured at the seat site. Flamsteed projections for four different flight conditions.

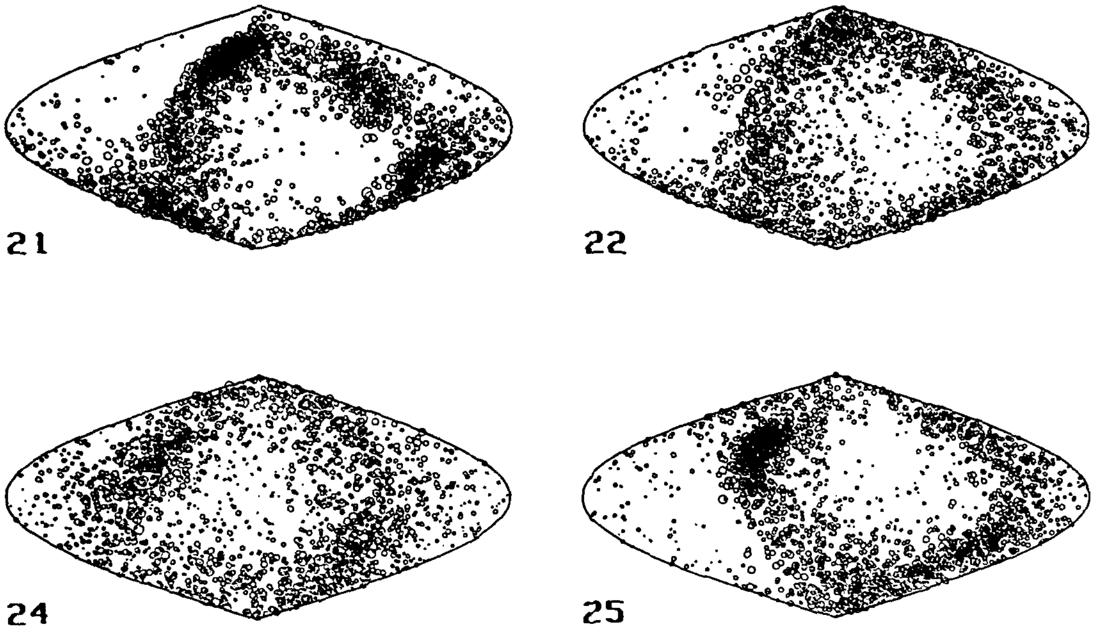


Fig. 3- Pattern of the addition of the three acceleration vectors measured at the backrest site. Flamsteed projections for four different flight conditions

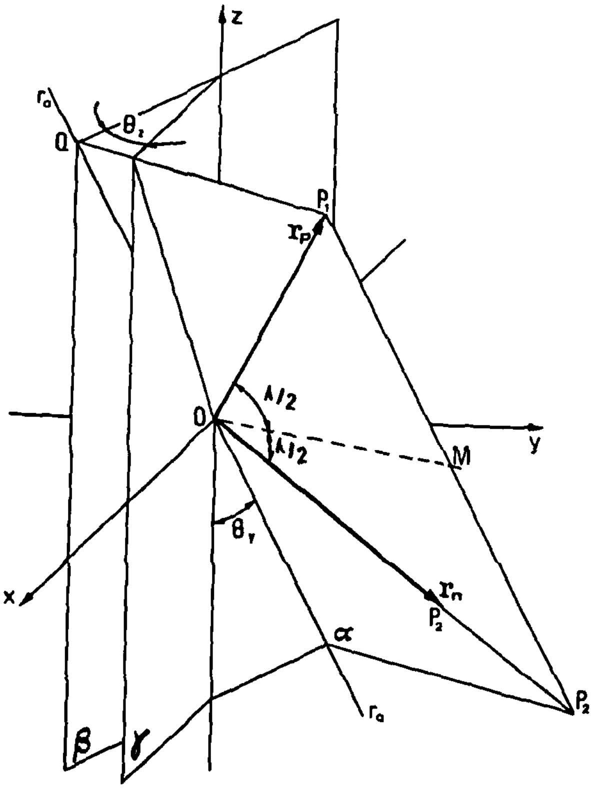
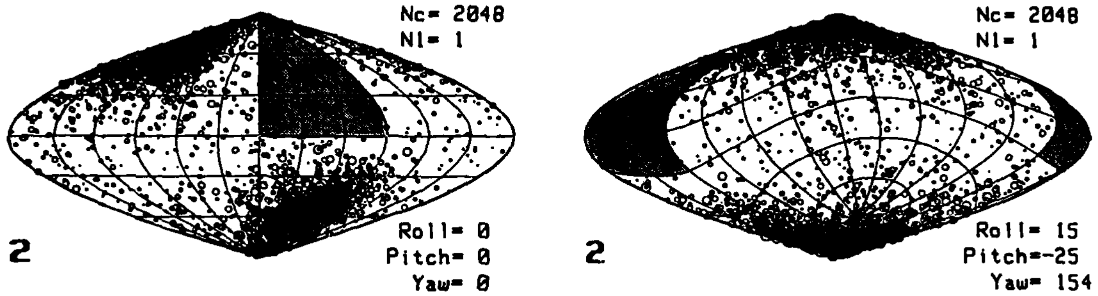
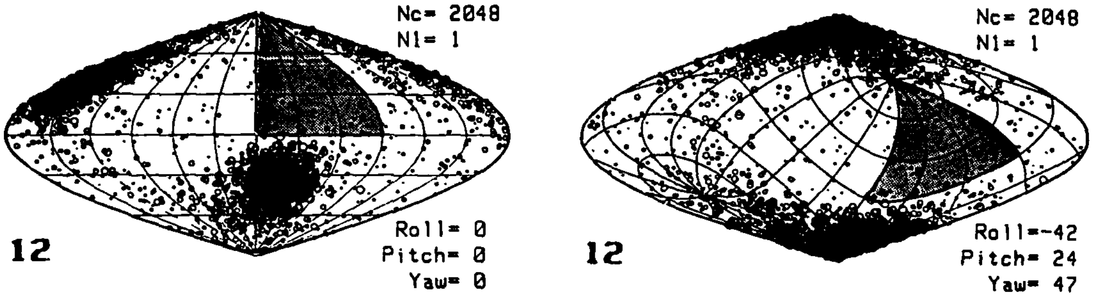


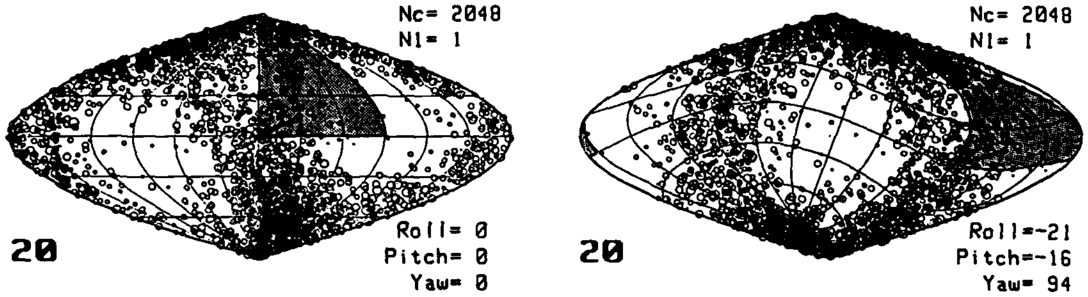
Fig. 4- Procedure for automatic reorientation of the frame of reference z. $\overrightarrow{OP_1} = \mathbf{r}_p$; $\overrightarrow{OP_2}$ $\mathbf{r}_n$; $\overline{OP_2'} = |\mathbf{r}_p|$; $\overline{MP_1} = \overline{MP_2'}$; $\overrightarrow{OQ} \perp \overrightarrow{OM}$; the vectors $\mathbf{r}_p$ and $\mathbf{r}_n$ and the line z_a belong to plane α ; the line z_a and z axis belong to plane β ; x and y axes belong to plane γ ; the angles θ_z and θ_y are direction cosines of the line z_a.



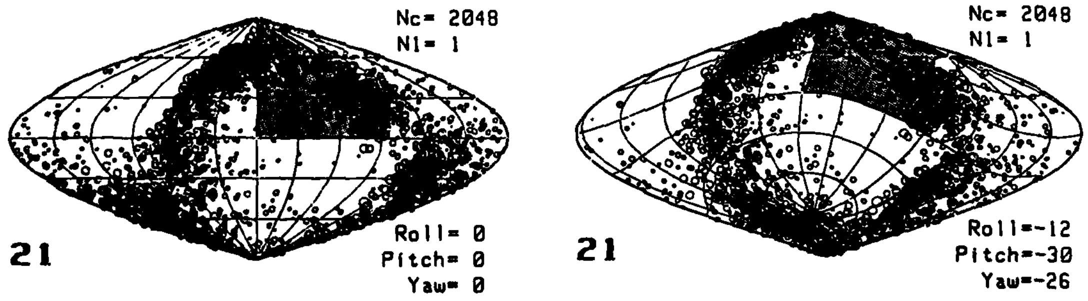
"just after the takeoff"



"vertical rate descent"

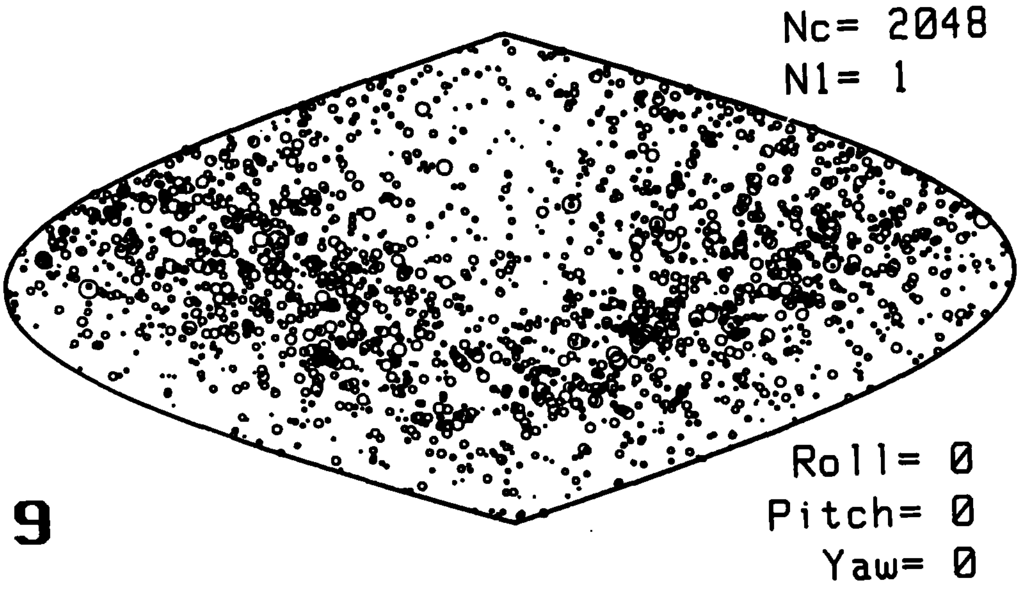


"translational flight (seat)"

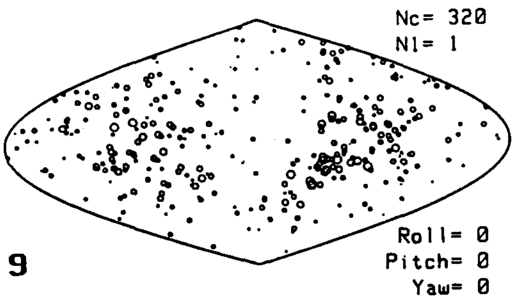


"translational flight (backrest)"

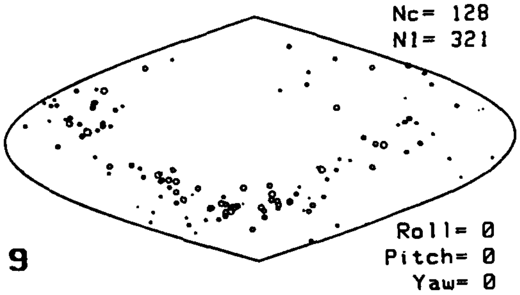
Fig. 5- Some examples of reorientation of the frame of reference. At the left, vectors r are represented with reference to the frame defined by the position of the thriaxial accelerometer. At the right, vectors r are represented with reference to the frame defined by the automatic reorientation.


Nc= 2048
N1= 1
9
Roll= 0
Pitch= 0
Yaw= 0

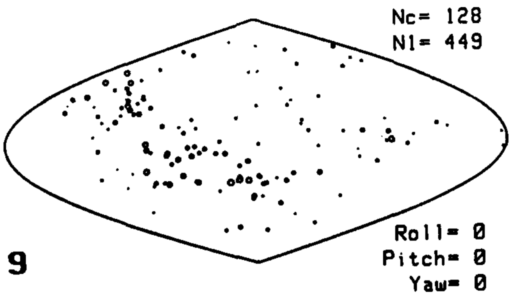
-a-


Nc= 320
N1= 1
9
Roll= 0
Pitch= 0
Yaw= 0

-b-


Nc= 128
N1= 321
9
Roll= 0
Pitch= 0
Yaw= 0

-c-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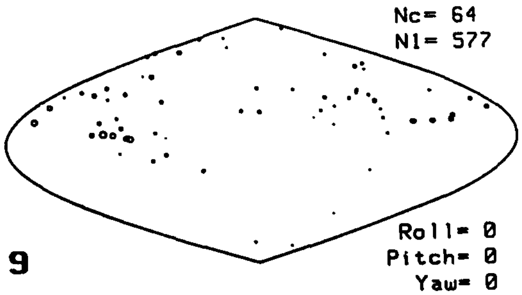
N1= 449
9
Roll= 0
Pitch= 0
Yaw= 0

-d-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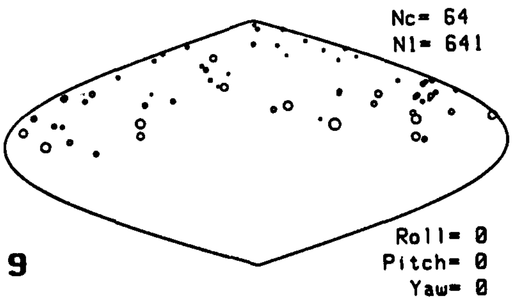
N1= 577
9
Roll= 0
Pitch= 0
Yaw= 0

-e-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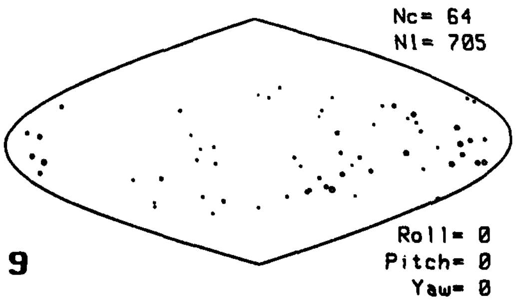
N1= 641
9
Roll= 0
Pitch= 0
Yaw= 0

-f-


Nc= 64
N1= 705
9
Roll= 0
Pitch= 0
Yaw= 0

-g-

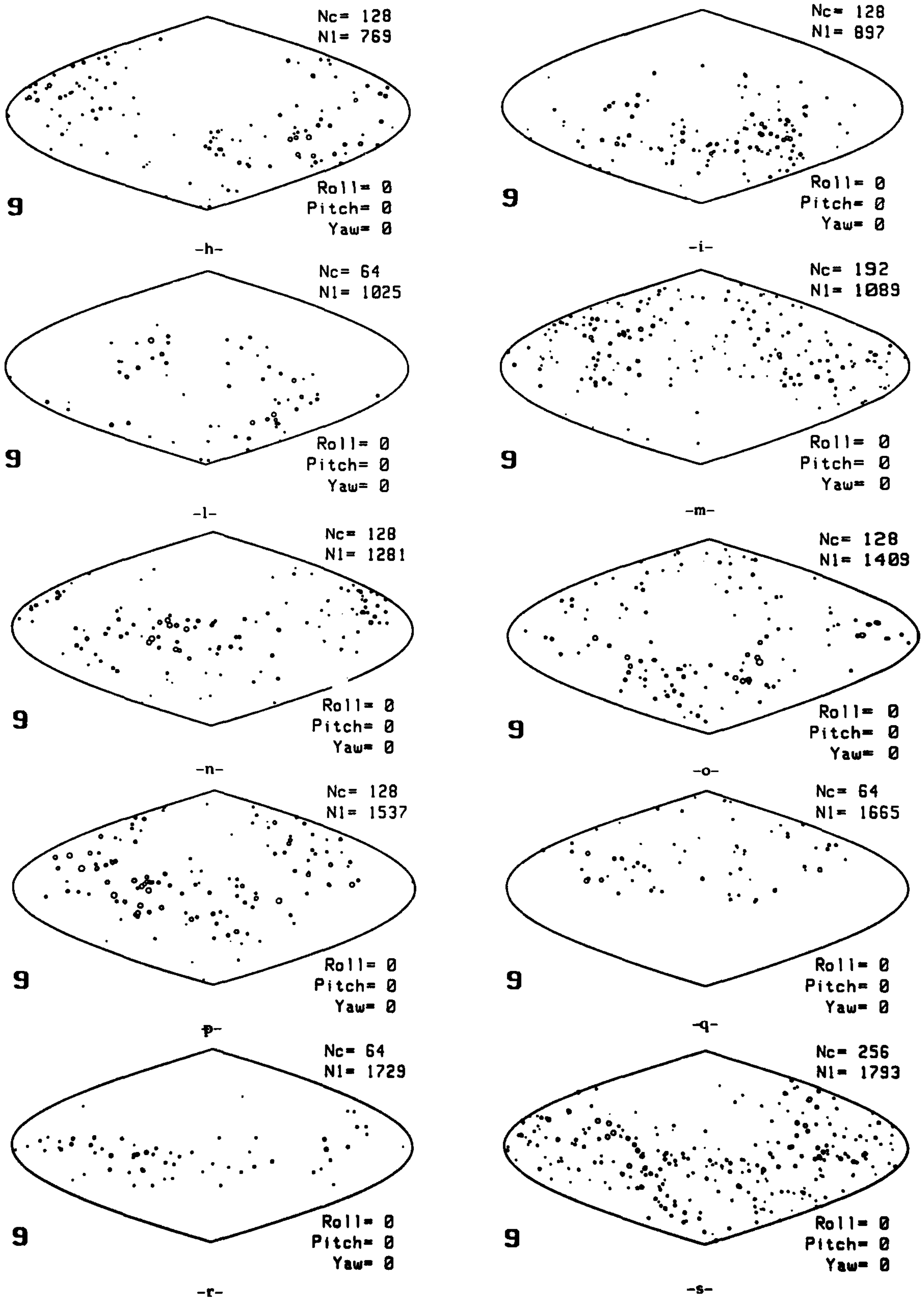


Fig. 6- Evidence that the orientation of the rotational motion is variable with the time. a: pattern of all the 2048 vectors which are of the measured sample; b...s: patterns of segments of the measured sample having different lenghts (all the pattern correspond to rotational motions,but the orientation of the spin axis is always different).

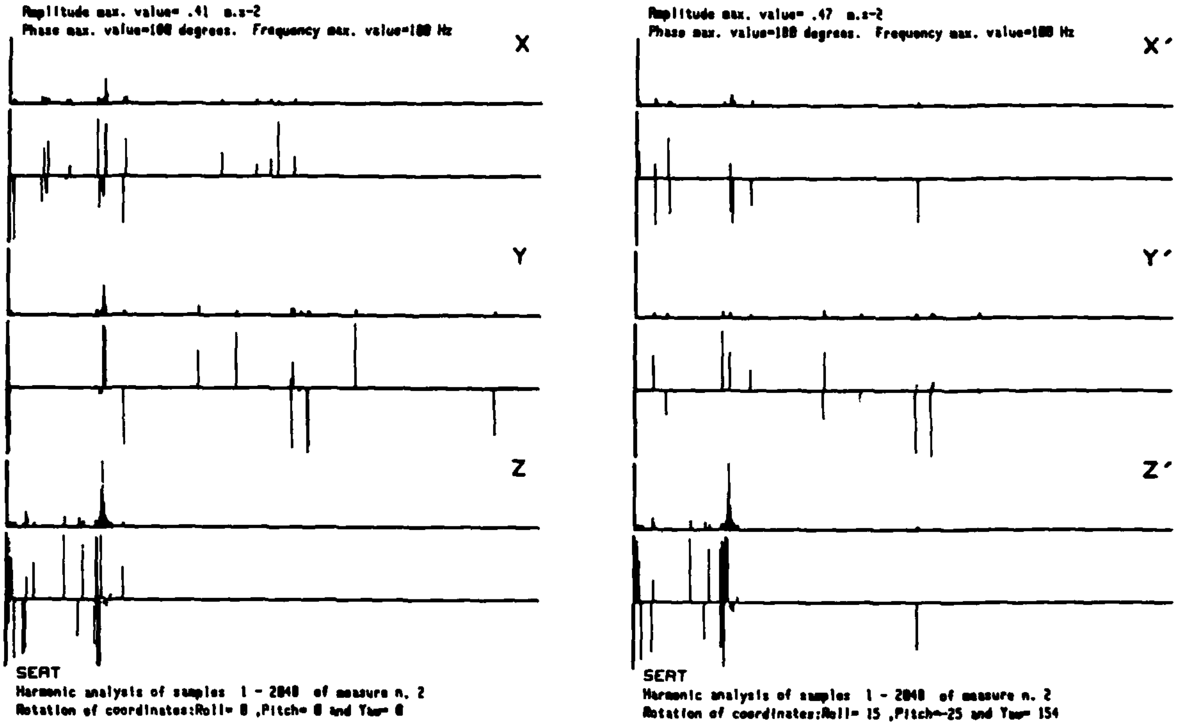


Fig. 7- FFT analysis of measurement n. 2 before (at the heft) and after (at the right) the reorientation. The measurement has been made at the seat site just after the takeoff.

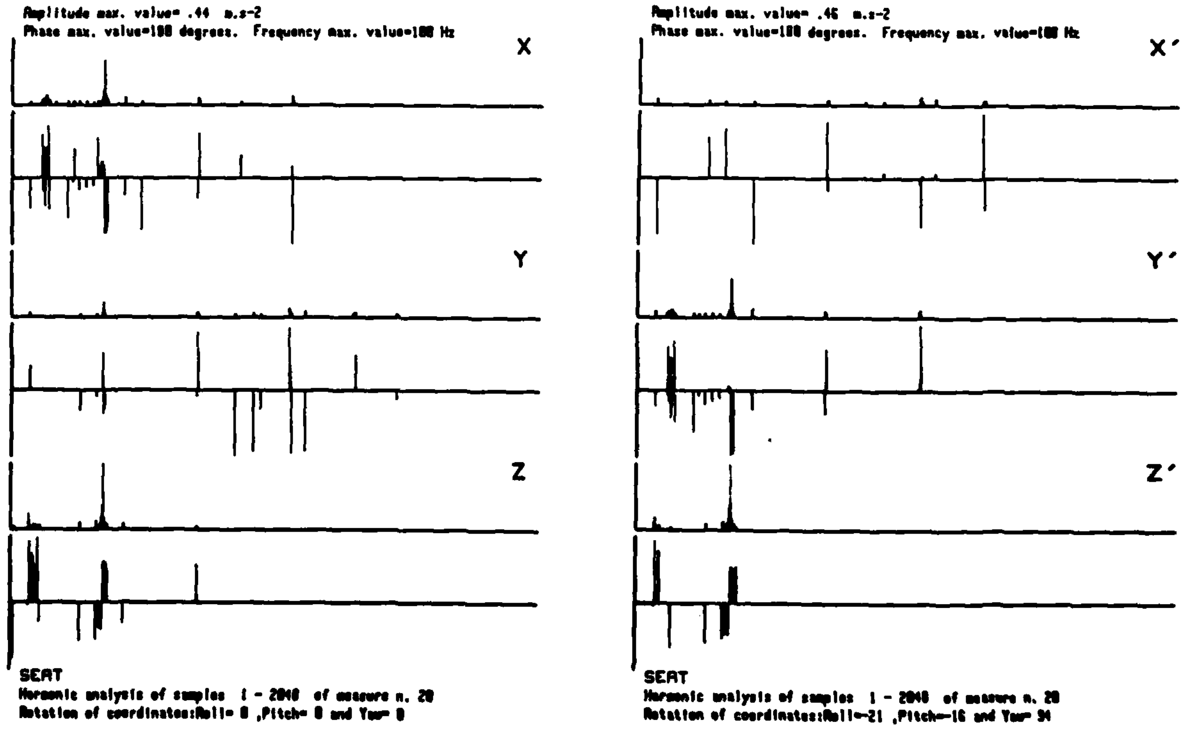


Fig. 8- FFT analysis of measurement n. 20 before (at the left) and after (at the right) the reorientation. The measurement has been made at the seat site during a translational flight.

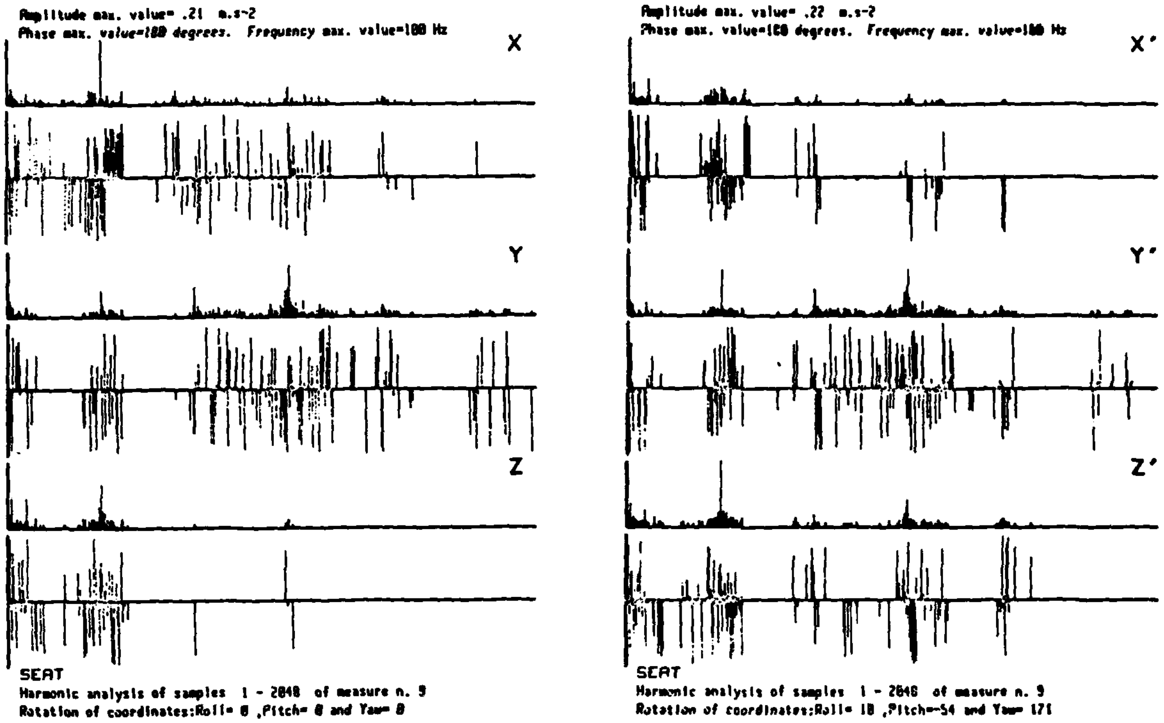


Fig. 9- FFT analysis of measurement n. 9 before (at the left) and after (at the right) the reorientation. The measurement has been made at the seat site during the hovering flight, with ground effect.

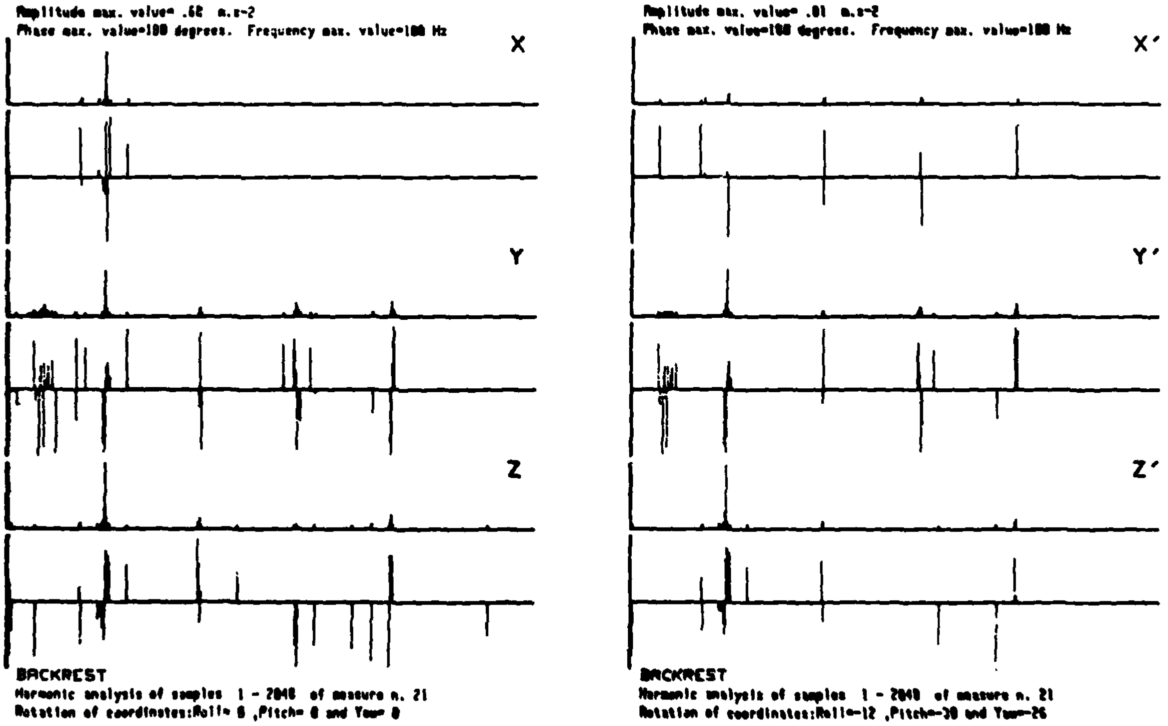


Fig. 10- FFT analysis of measurement n. 21 before (at the left) and after (at the right) the reorientation. The measurement has been made at the backrest site during a translational flight.

DISCUSSION

BOWDEN, CA: The Flamsteed projection was used in your paper. I am familiar with the name of Flamsteed as the English Astronomer Royal, but I am not familiar with the mathematical description of his projection. Is it the simple unfolding of the spherical surface onto a flat plane centered at one axis?

ANTONINI, IT: He was the famous astronomer, who was the first director of the Greenwich Observatory. The mathematics of this projection is not very complicated. The important thing to understand is that it is just an unfolding, a way of mapping a sphere onto a plane. It gives an idea of how a movement in a three-dimensional space can be mapped onto a plane; and allows you to reduce from three dimensions (which is impossible to understand on paper) to just two dimensions. It is quite a common way to do that.

BOWDEN, CA: You described rotary motion; and, I believe, you explained this as accelerations in which the two components in the planes were out of phase. Can you extend your analysis or representation to include truly rotary motion; i.e., motion of the rigid seat about an axis? This has been considered as a component of vibratory stress in biomechanics. Have you explored this problem?

ANTONINI, IT: We took into account only the problem of representing a movement in space for the medical investigator, who is usually unfamiliar with mathematical concepts. This method gives him an idea of movement in space. Obviously, this method can be applied to any moving vector, e.g., a vector cardiogram, for stress analysis in aircraft design projects, etc. It is just a way to represent a vector on a plane.

MEASUREMENTS OF CHANGE OF STATURE IN THE ASSESSMENT OF STATIC AND DYNAMIC SPINAL LOADING

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Summary

The height of the body in the erect position varies by about 1% during the course of the day. It decreases rapidly on getting up and, depending on the pattern of work and rest, continues to reduce during the day, but recovers overnight. With conventional methods of measuring stature, these changes would go unrecognised. Apparatus has therefore been developed allowing measurement to an accuracy of at least 1 mm. Studies have been made of static loading, lifting, running, in different types of seating and in resting postures. In general, height losses are proportional to the magnitude of lumbosacral compression. In addition, height losses from exercise are related to the perception of the exertion involved; and the gains in height produced in positions of rest are proportional to ratings for relaxation or comfort. For the ergonomist, therefore, the method offers a reliable means of assessing the effects of work and recovery on the spine.

Introduction

The diurnal changes in stature arise mainly from loss and regain in the height of the load-bearing structures of the body, mainly that of the intervertebral discs which, in the healthy spine, amount to about a third of the length of the vertebral axis. Disc height is reduced whenever the spine is loaded enough for the intradiscal pressure to exceed the osmotic pressure in the tissues of the disc. Fluid is then expelled. When the compressive load is relieved, fluid is imbibed and the height regained.

One of the first to consider the relation between backache, working posture and spinal loading was Fitzgerald (1972): he developed an apparatus for measuring stature and studied the effects of spinal loads, using aircrew as subjects. But when his apparatus was copied, attempts to reproduce his results were a failure. The reason appeared to be that the original measurements were made not only with the subject standing erect, but against a strictly vertical surface. In subjects whose backs are not remrod straight, this requires some static muscular effort, relaxation is difficult and repeatable results are elusive. The method now adopted is therefore to assess the subjects' maximal, but unstrained, standing height and observe the spinal posture. Support is given in a number of positions between the head and the sacrum and their vertical heights and horizontal positions are noted for repeat observations. The subject is then tilted back by between 5° and 15°, so allowing maximal standing height to be maintained under relaxed conditions.

The method has been developed in a series of collaborative studies in the Department of Orthopaedic and Accident Surgery, University of Liverpool; the Department of Sport and Recreation Studies, Liverpool Polytechnic; the Department of Production Engineering and Production Management, University of Nottingham; and the Division of Industrial Ergonomics, Linköping Institute of Technology, Sweden. As procedures and apparatus have improved, minor technical changes have been, and continue to be, introduced but the method to be described has been used consistently throughout.

Method

The apparatus consists of a rigid vertical framework with a platform on which subjects stand and a measuring device applied to the vertex. The vertical heights of each of the supports for the body and of the measuring device are all adjustable, likewise the horizontal projection of the supports, and their positions recorded for each subject so that they can be reproduced for later observations.

Subjects stand with their heels in fixed positions, their feet straight and the medial malleoli against a wooden block between the feet. Body weight is evenly distributed between heels and forefeet using weighing scales, which are fitted flush with the platform, under the forefeet. Knees are straight but not tensed. Supports are provided at the levels of the sacrum, the hollow of the lumbar curve, the mid-thorax, the hollow of the neck and at the occiput. Each is provided with a microswitch so that when all switches read 'on', the subject's posture has been precisely reproduced. The tilt of the head is controlled using a spectacle frame and visual guidelines.

The measuring device is a displacement transducer based on a spring steel reed fitted with strain-gauges but, in addition, a dial-test micrometer is fitted to provide the observer with a visual check. This device, which is mounted on a vertical rod with free-running bearings and counter balanced to avoid excessive pressure on the head, is then lowered into position. When all microswitches are on, head position and weight distribution of the feet are both correct, the measurement is made.

Some training is needed: first, to establish the comfortable, maximal standing height and the associated spinal posture; and secondly, to accustom subjects to the procedure. In order to complete the standardisation of posture, it is prudent to control the respiratory cycle. Subjects stand with arms folded and the measurement is made, generally at the end of a normal expiration. The duration of training varies from 20 to 90 minutes, depending on the experience of the observer and the response of the subject to the testing environment. In all the studies reported, repeatability of the measurements has been assessed for each subject in successive observations, subjects stepping out of the apparatus between each measurement. For example, Tyrrell et al. (1985) found that individual standard deviations for 10 consecutive measurements ranged from 0.05 to 0.46 mm and Leatt (1984) found that in two groups of subjects, standard deviations averaged 0.36 and 0.33 mm respectively. In no individual did accuracy fall below 1 mm.

Results

Circadian Variation

Eklund & Corlett (1984) measured stature at three hourly intervals from 1½ hours to 10½ hours after rising and recorded a mean height loss of 6.3 mm. To simulate the effects of sleep, subjects lay down for two hours after which they had regained 7 mm. Reilly et al. (1984) measured 8 males, aged 19-21 years and recorded stature over a 24 hour period from 2000 hours, at midnight just before going to bed, 0345, 0730, 0815, 0900, 1000, 1200, 1600 and again at 2000. The peak to trough variation was 19.3 mm or 1.1% of overall stature.

Static Spinal Loading and Recovery

Using a shoulder load of 14 kg for one hour, Eklund & Corlett (1984) reported an increase of 1.8 mm in the height lost compared with one hour's similar activity without the shoulder load. In a further experiment, the height lost in a 1 hour period of standing was 1.5 mm. Immediately afterwards, subjects held a 14 kg weight in one hand for 30 minutes and a further height loss of 2.7 mm was recorded. They then lay down for 15 minutes and regained 2.5 mm.

Tyrrell et al. (1985) reported the following losses for 8 subjects after holding barbells on the shoulders for 20 minutes:-

10 kg	20 kg	30 kg	40 kg
5.1 mm	7.1 mm	9.4 mm	11.2 mm.

The subjects recovered in the standing position and after 10 minutes had regained all but about 2 mm of height lost under the shoulder loads. Recovery after a shoulder load with a 10 kg rucksack was studies in both standing and in Fowler's position (supine but with hips and knees flexed and the legs supported). Following a loss of 5 mm, 4 mm was regained after 10 minutes standing, but 6.5 mm in Fowler's position.

Using a waistcoat with pockets for lead weights in experiments at Linköping (Troup et al. 1985), shoulder loads of up to 25 kg were applied for 45 minutes and, in addition, vertical traction of 10 kp force was applied via a pulley to a belt round the chest. In all five modes used (-10, 0, +10, +20, +25) the forces were evenly distributed front and back. Apart from the result for the '-10' mode there was a significant relation between height lost and shoulder load. The vertical traction of 10 kp did not apparently unload the spine. When the changes in stature were plotted against the discomfort ratings obtained, there was a good correlation. The height changes and the discomfort ratings were as follows:-

'-10'	'0'	'+10'	'+20'	'+25'	
2.03	1.76	2.48	3.41	4.14	(mm height loss)
281	40	182	427	511	(summarised ratings).

Lifting Exercise and Recovery

Tyrrell et al. (1984) studied the effects of 20 minutes lifting at a rate of 12 lifts per minute with 20 second breaks every 2 minutes, using 10 kg and 40 kg barbells. The height losses were 6.9 mm and 14.5 mm respectively: significantly more than for static loading with the same weights. In the 10 minutes after 40 kg lifting, 8.4 mm was recovered in the standing position. In the 10 minutes after the 10 kg lifting, 6.8 mm was regained in the standing position but 7.6 mm in Fowler's position.

Running

Height losses were measured in 9 inexperienced and 7 experienced runners before and after completion of a 6 km treadmill run at 12.2 km/hr (Leatt 1984; Troup et al. 1985). In the last minute of each run, subjects rated their sensation of perceived exertion. The inexperienced group lost 3.3 mm and the experienced, 2.4 mm: the difference was not significant. But when height losses of the inexperienced runners were plotted against perceived exertion, there was a significant correlation (p 0.05).

Gravity Inversion

Regain in stature was studied after subjects had lain, held by the ankles, in supine postures at angles of inversion of 50°, 70° and 90°, but also in Fowler's position (Leatt 1984; Troup et al. 1985). Although there were no significant differences between heights gained in the four positions, the greatest gain was an average of 5.6 mm after 30 minutes at 50° inversion. Subjects were questioned about comfort and relaxation and the data from all four experiments were pooled. Those who had felt uncomfortable gained the least height. While subjects who reported the most relaxation maintained their height gains in the standing position which followed, more than those who had not felt relaxed.

Sitting

Eklund & Corlett (1984) compared losses in stature after sitting for 1½ hours: on a stool without backrest, on an office chair and in an easy chair. In the latter two chairs there were no significant changes but on the stool, subjects lost an average of 4.6 mm. They then compared the effects of performing a light pushing task while seated, with and without a backrest. Subjects pushed on a lever with alternate hands, exerting a horizontal force of 25 N for 30 minutes. Without the back rest, subjects lost height but with it they gained height; suggesting that with the backrest, pushing enabled them to unload their spines.

Discussion

Although this method of measuring stature has proved remarkably accurate, nearly all the subjects used in the experiments reported here were young, healthy males. The next stage in this series is to enlarge the experience by observation of a wider range of the population. Preliminary results from a series of young females suggests that their is no substantial difference in the responses to loading between the two sexes. Older and stiffer subjects have yet to be studied. But what remains uncertain is the proportion of the population and of its sub-groups who are resistant to measurement. The possibility that some people will prove immune to repeatable measurement must be foreseen.

Nevertheless, the method has a very clear potential in ergonomics and occupational health. The fact that changes in stature have been shown to relate not only to biomechanical but to psychophysical factors is highly significant. With small groups of subjects, the effects of exercise and recovery can be studied in periods of less than an hour and the effects of sedentary work in periods not much longer. Great care, though, is needed to standardize the timing of observation. The circadian variation itself represents the largest single factor so far recognised and in all the studies quoted, observations have been made at the same time on each day of measurement.

The typical model for circadian variation in stature (Reilly et al. 1984) shows a smooth exponential curve as the rate of height loss slows in the course of the day followed by a rapid recovery after going to bed. But it is evident from these studies that there are major departures from this model as periods of activity and rest-pauses interweave through the day. It has, of course, been foreseen that in the morning a given loading will have a greater effect in reducing height than the same load late in the evening and preliminary experiments in females have confirmed it (Wilby 1985). It is possible that the problem of how to make observations at more or less any time of the day can be overcome by imposing a standardised period of rest beforehand, but this needs further investigation.

In conclusion, it should perhaps be remembered that interest in this subject arose from Fitzgerald's concern with the relation between back symptoms and sedentary postural stress. It has to be admitted that, as yet, we know rather little about the relation between symptoms and reductions in stature. Though the method has any number of ergonomic applications right now, there are many clinical problems still to be solved.

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DISCUSSION

AKKERVEEKEN, NE: Was the discomfort rating according to that of Corlett and Bishop (Ergonomics 19: 175-182, 1976)?

TROUP, UK: Yes,

SANDOVER, UK: You mentioned the effect of age on the method. I assume that this is due to the fact that the disc is changing its characteristics. Could you comment on how that affects the measurement?

TROUP, UK: My comment on age related to the previous studies of stature by Kramer, in Germany. We have only got one small sample, but, nonetheless, it confirms that there are age-related changes. The significance, supposing that we want to look at changes in stature in 55 year-olds, so to speak, is that we may require rather more subjects, depending on how repeatable the measurements are, because they will probably have a maximal diurnal variation of, shall we say, 60% of that of younger people. (It may be that, but we don't know these figures yet. That is why we still have a few more studies to do to fully validate our method for all types of population.)

SANDOVER, UK: Is this all to be done on young subjects?

TROUP, UK: Mainly, yes.

SINGER, PO: I would like to ask two questions. The first question is whether the height losses are homogeneous in all vertebral segments, or if there is any segment which may be affected more greatly? The second question is: "Physiotherapists often use distraction to alleviate lumbar pain. Must we understand that height loss has nothing to do with height gain, notwithstanding the clinical benefit?"

TROUP, UK: With regard to the homogeneity of height losses at different levels of the lumbar spine, I can't answer your question. So far, we haven't developed a technique for looking at the height loss at different levels; and I think, almost certainly, that radiography would be far too insensitive. We can only assume, or state a hypothesis, that the height loss will be somewhat greater, relatively speaking, in the lumbar region simply because of the higher biomechanical loading. Of course, we have to take into account the area of the disc under load. My answer to your question is: "No we don't know". Your second question concerns the effects of therapeutic traction. I think the lesson from what we have learned here is that, if you believe in traction, and if you believe in postures which take the load off the spine, then both the traction which you apply and the positions in which you put the patient must be comfortable. I am sure my physiotherapist would agree with me that, if you apply traction and the patient is not comfortable, then you are not going to do them any good.

BACKACHE IN AIRCREW

by

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SUMMARY

Aircrew have long complained of backache. The backache is seldom severe, but frequently interferes with flying performance and is very distracting. A survey was conducted amongst UK aircrew in 1971 which showed that aircrew suffer from backache twice more frequently than groundcrew, pilots suffer more than other aircrew members and that ejection seats caused more backache than other types of seats. The survey also showed that half the aircrew never suffered from backache on the ground. The incidence of backache was high, 13% of pilots suffered on every flight, 22% suffered once a week whilst 45% suffered once a month.

The backache is caused by the sitting position and design of the seat, which leads to loss of the lumbar curve. When the lumbar curve is restored by means of a curved rigid pad applied to the back, 50% of aircrew report that the backache is greatly improved and in 32% of cases completely resolved.

A scheme has been underway for some years in the UK to provide lumbar pads for aircrew complaining of backache. The pads are simple and cheap to produce and are easy to use. However, the major disadvantage is that they require a mould for the individual's lumbar curve and then they cannot be used by other aircrew. This disadvantage aside, the scheme has been a success and will be continued.

Aircraft seat designs both for ejection seats and helicopter crew seats now incorporate lumbar support curves to prevent both loss of the lumbar curve and the subsequent backache in aircrew. The incidence of backache in aircraft incorporating these new designs is considerably lower.

INTRODUCTION

Low back pain must be one of the most common complaints of civilized man. Much of this is due to his erect position combined with the requirements, in many occupations, to carry heavy loads with the back flexed, a poor posture for load carrying. In addition, sitting for long hours at poorly designed workplaces can aggravate this complaint. Amongst these workplaces must be included the cockpits of aircraft where the requirement to fit all the controls and instruments in a small space has left insufficient room and comfort for the aircrew to operate successfully.

Thus backache in aircrew is very common and has been accepted for some time because aircrew rarely have received much relief and sometimes their career depended to a certain extent in its acceptance as an occupational discomfort. Aircrew are often loath to seek advice if grounding could be considered as treatment.

Backache in aircrew can be defined as pain in the mid line of the lower back, usually without radiation, which occurs in flight and may persist afterwards. The severity and incidence is variable, it can occur on every flight commencing minutes after strapping-in in severe cases, or be just mild discomfort only after some hours in the aircraft and then only during intensive phases of flying.

BACKACHE CAUSATION

Fitzgerald (1968) first examined the problem of backache in aircrew in the UK. He described the anatomy and physiology of the lower lumbar spine and how lumbar lordosis (ie an anterior convex curve) was acquired in childhood. As the standing posture is achieved and the legs extend, the hip joint flexors do not extend completely and this tilts the sacrum forward. To regain the vertical, the lumbar spine curves backwards and causes lordosis.

The spinal posture is dictated by the pelvic angle and is a function of muscle tone, ligamentous support and efficient proprioception. When sitting, the gluteii and posterior thigh (hamstring) muscles are stretched and they tilt the pelvis rearwards. This flattens the lumbar curve, reduces the lordosis and directs pressure on the anterior portions of the intervertebral discs. In compensation, the discs bulge posteriorly and stretch the posterior longitudinal spinal ligament which is very pain sensitive. When seated in an aircraft for some hours, particularly when strapped to the seat which restricts all movements, the para-vertebral muscles become fatigued and the loss of lordosis becomes marked. This causes tension of the posterior longitudinal ligament which can be quite severe. Chronic exposure to this position causes damage to the disc and associated ligaments and the associated pain can cause spasm of the erector spinae and hamstring muscles. The pain and discomfort can only be relieved by leaving the seat and stretching and flexing the lumbar spine, however the discomfort can persist for some hours.

On the other hand, a position of comfort is obtained where the antagonistic anterior and posterior thigh-trunk muscle groups are balanced at about a thigh-trunk angle of 135°. This is the angle adopted in sleep. This angle can be attained in some easy chairs but never in aircraft where the feet are required to control rudders and space is at a premium which requires an angle of 90° or less. Interestingly, some new typist chairs are being marketed where 135° can be achieved by balancing pressure on the front of the shins to that on the buttocks. However, this concept is of little use in most aircraft because the feet could not control the rudder pedals in that position.

Aircraft seats require a trunk-thigh angle nearer 90° and often induce a leaning forward position as parachute packs are positioned behind the shoulders. The combination of pelvic tilt and thoracic forward flexion eliminates the lumbar lordosis and discomfort or pain results. The nature of the sitting platform itself can further aggravate the problem. If the platform is too soft, the ischial tuberosities will sink into the cushion and further decrease the thigh to torso angle and cause more pelvic tilt. A rigid flat platform will also cause discomfort as all the weight is supported by the tuberosities and the local high pressure will be painful. However, a rigid but shaped panel, following the contour of the buttocks and ischial tuberosities will be more comfortable because the rigid platform will prevent further thigh-torso flexion, and the contoured surface will redistribute the sitting pressure over a wider area.

ALLEVIATION OF BACKACHE

Fitzgerald (1968) noted that given the deficiencies of many aircraft seats, an effective remedy would be to reimpose the lumbar lordosis by means of a pad placed behind the lumbar curve and resting against the vertical surface of the seat back. This pad should be between 5 and 25 mm thick but no single measure would suffice for all. When aircrew sat on a bare sitting platform and rested their backs against a vertical flat surface, he observed a gap between the skin over the lumbar spine and the seat back. Rarely was this gap more than 25 mm and in a few cases there was no measurable gap at all. However, the majority exhibited a space between the seat back and lumbar curve and when a pad was introduced into this gap, it supported the lumbar spine and gave considerable symptomatic relief especially to those aircrew who had earlier complained of backache in aircraft.

The variability of this gap lead Fitzgerald and co-workers to devise a concept of custom fitting lumbar pads. However, a method was required to record the contours of the lumbar curve in relation to the seat back before these pads could be made. In 1965, Fitzgerald, Sharp and Barwood described a method of casting body contours by using polyvinyl chloride or polystyrene spheres in a flexible container moulded to the contour of the back. The contour was held in that shape by evacuating all the air from the container so that the spheres coalesced. This rigid contour could then be used as a mould for a pad made of fibreglass which when prepared was an exact replica of the contour of the individual lumbar curve. By permitting air to re-enter the container of the plastic spheres, the device could be used many times.

BACKACHE SURVEYS

This device was used to produce some 50 lumbar pads for aircrew who complained of backache in flight. Early reports were most encouraging. Only one of the fifty received no benefit but he had sustained severe spinal injury earlier. Another pilot who reported only slight improvement had early ankylosis spondylitis. Of the remaining, 62% reported complete relief and 34% admitted marked improvement of their symptoms. A later survey (Fitzgerald, 1973) of the use of 200 such lumbar supports showed that 50% of the users were symptom free and 31% had a marked improvement. However, before the use of such lumbar supports could be justified as a routine, a survey of the extent of aircrew backache was required. This was conducted in the RAF in 1970. Fitzgerald and Crotty (1971) reported on a questionnaire survey of some 2000 aircrew and groundcrew. They found that backache was twice as common in aircrew than groundcrew, pilots complained more than other aircrew, pilots using ejection seats complained of backache more frequently than those using fixed seats and that helicopter aircrew suffered most of all. More than half of the pilots who complained of backache never suffered from backache when they were not flying. In particular, 13% of RAF pilots experienced backache every time they flew, 22% suffered from backache or back pain once a week when flying, whilst 40% developed back pain at least once a month. The backache was also associated with fatigue, irritability, distractions in flight and interfered with post-flight sleep and relaxation.

The data retrieved permitted a 'black list' of aircraft to be produced with the worst incidence and persistence of symptoms. The Canberra T Mk 4 with a very unergonomic position of ejection seats took worst position, next came the Jet Provost with its bulky parachute pack just behind the shoulders and soft seat cushion, then the Vulcan and Victors where the long duration of the sorties clearly added to the problem. Amongst the helicopters, Fitzgerald and Crotty (1971) singled out the Whirlwind Mk 10 and Wessex Mk 2 as worst offenders. The Whirlwind because of the necessity to lean forward to obtain sufficient forward vision under the top of the windscreen and the Wessex because most respondents felt that some degree of reclination to offset the forward tilt was required.

Backache in Helicopters

The backache complained of by helicopter pilots is different in character and position from that caused by other aircraft and is due to other mechanisms. When controlling a helicopter, the right arm which grasps the stick is rested on the right thigh to prevent any vibrations of the helicopter moving the right arm holding the stick. In order to do this the pilot must bend forwards slightly and tilt to the right. At the same time, both feet are required on the rudder pedals and pressure is required during flight to adjust the thrust provided by the anti-torque tail rotor. This pressure decreases the pelvic tilt as the force transmitted by the legs pushes the upper part of the pelvis rearwards. The left hand meanwhile holds the collective lever as this controls the pitch and thus the power output from the main rotor. To reach and lift up the lever the spine must rotate to the left. This scoliosis and twist of the spine produces pain on the left side at the junction of the thoracic and lumbar vertebrae. A second area of pain at the level of the right shoulder blade is caused by the effort to extend the right arm to the stick. The pelvic position reduces lumbar lordosis but increases discomfort.

Furthermore, the nose down attitude which helicopters usually adopt in flight, especially with underslung loads, tends to throw the pilot forward out of his seat. Any compensatory tightening of the shoulder harness further distorts the spinal curves. Thus helicopter pilots have more florid symptoms and pain higher up the spinal column than their fixed wing brethren.

A later survey examined backache in the Gazelle helicopter (Braithwaite et al 1981). They found that 57% suffered backache on flights lasting more than one hour, 18% had backache after intensive flying (20 hrs in 10 days), 11% noted backache during some flights whilst 8% suffered during most flights. 77% of all respondants found the Gazelle seat uncomfortable. They recommended, amongst other features, that additional lumbar supports be provided by an adjustable pad, that the seat be reclined by 5-10° and that lumbar pads be provided for Gazelle aircrew.

LUMBAR SUPPORTS

Since 1971, lumbar supports have been offered to all aircrew in the RAF with lower backache and their use continues to grow with gratifying results in the attenuation of symptoms.

The lumbar supports are made using the procedure originally described by Fitzgerald (1973) with a few later refinements. The procedure for issue is as follows.

The first step for a complainant is to approach his Service Medical Officer. The Medical Officer will examine the patient and if he is convinced that the backache is postural in origin and not due to underlying pathology he will request an appointment at the Royal Air Force Aviation Medicine Training Centre (AMTC) at RAF North Luffenham in Leicestershire, UK. On receipt of the request, an appointment is offered and the patient attends for fitting. The history is confirmed, acute cases are delayed for resolution and in patients with severe pain and/or spinal spasm, treatment is postponed. A special fitting seat is prepared to which can be fitted a rubber blanket containing a permeable tightly-woven cotton pad filled with many small spheres of polystyrene. To contain the spheres laterally, the pad is seamed vertically at 25 mm intervals and closed top and bottom.

Fitting

The patient strips to the waist and belts and other bulky articles are removed. He then sits in the fitting seat in a position of comfort so that the Medical Officer can view his lumbar curve from the side. He then decides whether the curve is adequate or requires restoration by assessing the subjective improvement of the patient when pressure is applied to the back. The patient then leaves the seat and the rubber blanket containing the polystyrene spheres is placed over the seat back. The blanket is carefully positioned then the patient sits in the seat and again is carefully positioned with respect to both seat and blanket. If the Medical Officer considers that the patients lumbar curve requires additional support, this is provided through the rubber blanket. Then, while this position is maintained, the air inside the blanket is evacuated by means of a small vacuum pump. This causes the polystyrene spheres to lock one against the other so that the patient may now leave the seat and the blanket can be removed as a rigid board but bearing an accurate imprint of the patient's lumbar curve. The blanket profile is laid on a work bench and examined for wrinkles, creases and other defects. If these are present, the blanket is inflated and the process repeated. When an accurate mould is obtained the patient dresses, is briefed about the use of the pad and the completion of a questionnaire into its utility. The lumbar support is despatched to him later.

Manufacture

The blanket is then used to make the lumbar support. Layers of glass fibre are placed on the blanket to flatten the interseam variations and a layer of mylar polyester film (5 microns thick) is placed on the glass fibre. Six further pieces of glass fibre are laid on the mylar and bound together with resin. The mixture is left to set for 24 hrs at room temperature. When the fibre glass is rigid it is removed from the blanket. The blanket can now be cleaned, reflated and used for another patient. The fibre glass is cut and trimmed to size (approx 300 mm square) and the patient's name and other details are incorporated into the back of the support including an indication of the 'top' of the support with respect to the wearer as the supports are never symmetrical across the horizontal plane.

A waist strap is made and applied and fixed to the support with epoxy resin glue. Then polyether foam is applied to the front surface, stuck and trimmed and covered with a Jersey cloth which is stuck around the edge of the support. After final inspection, the support is dispatched to the patient.

Instructions for Use

The patient is instructed to use the support whenever he flies and in any other seat, be it car or theatre, that aggravates his backache. He is cautioned never to lend it to another sufferer as it is personal to him, neither is he to use one made for another. On rare occasions, the support gives very good relief initially which then disappears. When this happens, the patient is asked to return for a check of the compatibility of patient and support. Sometimes the action of the support assists the lumbar spine to such an extent that the lumbar curve changes radically and another support shape is indicated. This second support always provides continued relief.

When the support is used together with an ejection seat, the support should be worn underneath the flying coverall to prevent the support flailing during the escape sequence. This will be reviewed in future ejection tests with a more effective method of attaching the support to prevent flailing. Recent combinations of Aircrew Clothing, particularly the use of an external anti-G suit, have prevented the support being worn under the coverall.

The Medical Officer at the patient's individual Station is asked to check the suitability of the support in the aircraft in question and also to supervise the return of the completed questionnaire detailing the patient's report of the effect of the support on his original symptoms.

Since 1976, the manufacture of aircrew lumbar supports has been undertaken principally at AMTC. Before that date all supports were produced at the RAF Institute of Aviation Medicine, Farnborough.

With the change of manufacturing location, a questionnaire was introduced and these provide a very useful source of data. Two hundred and thirty-nine supports have been made at AMTC up till December 1984.

QUESTIONNAIRE DATA

Each support was despatched with the questionnaire for completion and return. However, not every questionnaire was returned as one would expect in such a voluntary system. However, a sufficient number were returned for analysis and the conclusions of the questionnaires returned during 1983 and 1984 are presented here.

In these two years, 85 supports were made and 31 questionnaires were returned. The questionnaires asked first about the frequency and severity of the pain experienced. 5 respondants (16%) complained of pain on every flight, 21 (68%) said it occurred frequently and 5 (16%) described as 'occasional'.

The duration of the pain was described as 'only during the sortie' by 3 (10%) 'for up to 4 hours after the sortie' by 12(39%), 'all day after the sortie' by 8 (26%) and 'longer than the day of the sortie' by 8 (26%).

The average of the flying hours flown since the lumbar support was issued was 40 with a range of 10-180 whilst the number of hours flown with the lumbar support was 35 average, range 10-90.

The handling of the support in the cockpit was described as 'no bother at all' by 20 (65%), 'no bother once I'd got used to it' by 9 (29%), 'a bit of a nuisance at first' by 1 (3%) and 'a nuisance all the time' by 1 (3%).

In the aircraft, 26 (84%) considered the positioning of the support 'took no time at all' and 5 (16%) thought it 'took a minute or more'. No one said it 'took far too long'.

Once the support had been positioned, 13 (42%) said the support 'did not shift', 17 (55%) said it 'shifted a little occasionally' and 1 (3%) thought it 'shifted considerably'.

During the flight 13 (42%) of aircrew were 'unaware of the support', 18 (58%) were 'occasionally aware of the support', but no-one was 'aware of the support to the point of distraction'.

The ability to control the aircraft was 'improved' in 4 replies (13%) 'unchanged' in 24 (75%) but never 'diminished'.

The sitting comfort with the support was 'greatly improved' in 16 (52%), 'improved' in 12 (39%) and 'unchanged' in 3 (10%). It was never reported as 'reduced' or 'greatly reduced'.

Using the support the backache had 'disappeared entirely' in 10 (32%) or was 'considerably less' in 20 (65%). It was never reported as 'present as before', 'worse' or 'much worse'.

The fatigue after the sorties was described as 'less fatigued than usual' by 18 (58%), 'about the same' by 12 (39%) but never 'more fatigued than usual'.

Some aircrew did not complete the questionnaire thus the percentages are approximate in some cases.

These data can be summarized as coming from aircrew with pain on the majority of flights which persisted for some time afterwards. They experienced little difficulty in handling or positioning the support and it moved little in flight. They were on the whole unaware of the support in flight and it did not affect their control of the aircraft. However, the sitting comfort was improved in the vast majority and all said the backache had either disappeared or was considerably less. There was less fatigue after the flight as a result of wearing the support.

The returns about flying hours showed that the improvements had lasted some 40 hrs on the average and that the supports had been worn for almost all that time. Many respondants said they used the supports to good effect in car and other seats.

Aircrew were also asked for their comments on any improvements they would like to see incorporated and many of these are sensible and are worthy of consideration. A washable cover was asked for and would certainly make it a more attractive item of flying clothing. A more ventile or 'cooler' covering material was often requested. The belt was sometimes described as too short or too thin and a better fastening than touch and close fastener would be an improvement.

The instruction to wear the support under outer clothing in ejection seats was difficult to comply with in some cases as the bulk of the support could not always be accommodated under an immersion suit; the trials to clear the support for external use mentioned earlier should help in this regard.

The helicopter pilots did receive considerable relief particularly in the case of the Alouette which has a very uncomfortable seat. The relief has been so noticeable that all UK Army aircrew proceeding to Cyprus for duty in Alouette helicopters are now issued with a lumbar support as a prophylactic measure even before they have flown the aircraft or complained of backache.

A good impression of the types of aircraft seats which cause backache can be ascertained by examining the numbers and types of aircraft flown by the aircrew asking for and issued with lumbar supports. An obvious exception is the Alouette where all aircrew receive the support as described above, because there is little feedback on how many Alouette aircrew actually use the support. The data show that all other aircrew do use their supports.

Over the years 1978-84, 162 supports in toto have been issued by AMTC to aircrew flying the following aircraft types:

Fixed Wing: Jet Provost 25, Harrier 11, Hawk 9, Phantom 9,
Canberra 8, Victor 8, Jaguar 6, Nimrod 6, Vulcan 4,
Buccaneer 4, Andover 3, VC 10 2, Bulldog 2, Hercules 2,
Hunter 2, Shackleton 1, Tornado 1, Lightning 1

Helicopters: Alouette 19, Gazelle 15, Wessex 13, Sea King 7,
Puma 3, Chinook 1

In the years 1983/84 which relate to the questionnaire data, the distribution was:

Fixed Wing: Jet Provost 13, Harrier 5, Phantom 4, Victor 4,
Buccaneer 3, Nimrod 3, Canberra 2, Hunter 1, VC 10 1,
Hercules 1, Tornado 1, Bulldog 1

Helicopters: Alouette 12, Gazelle 8, Wessex 7, Sea King 7, Puma 3

The Jet Provost holds first place in the fixed wing fleet while the incidence of discomfort in the Gazelle has changed little since Braithwaite et al (1981) did their earlier survey.

These data also confirm that the design of modern ejection seats has done much to alleviate backache. In the Mk 9 and 10 series of Martin Baker seats, the lumbar profile which has been offered to backache sufferers has been incorporated into the seat back rest. Although not an individually moulded contour, it does feature both vertical and horizontal curvatures and it approximates the mean lumbar curve of all aircrew.

Thus in the Harrier, Jaguar, Tornado, Hawk and Sea Harrier there were comparatively few demands for supports, given the size of these aircraft fleets. With the predominance of these aircraft now in service one would have expected many more than in the Jet Provost fleet which is only used in training. The better design of ejection seats is now reducing the demand for lumbar supports from fixed wing aircrew. Unhappily, one cannot say the same for helicopters.

It is expected that the demand for lumbar supports from helicopter aircrew will continue until helicopter seat design incorporates the principles of lumbar support which have been shown to be so beneficial.

Even when the seats of both fixed and rotary wing aircraft are designed on sound ergonomic principles, it is still expected that some aircrew will need additional lumbar support to relieve their backache in flight.

Happily, there is a simple, cheap and reasonably quick way to offer relief in the shape of an individually moulded lumbar support and it is foreseen that these will be requested and supplied for many years to come.

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DISCUSSION

WILDER, US: The back rests that you have designed are moulded, based on the seated posture of the pilot in question. Have you given any thought to possibly providing more lordosis, or a greater curvature than is seen, just as when they are seated in your moulding apparatus?

READER, UK: I didn't design the back rests; their design, in fact, predated my activity. I carry on the business of producing them now. As I said in the talk, if we find that a pilot comes to us with backache and has lost his lumbar curve, it is important to reinstitute it by means of pressure, subtly placed, on a subjective basis. When we do that then, of course, we are increasing the curvature beyond what was shown at the time of consultation. Then, when that curve is introduced, it, of course, produces the desired effect. It is an important part of the selection process that, when a pilot first presents himself for a lumbar support, his lumbar curve is checked, because, if a person comes with a flat curve, and you mould the back rest to that curve, you will see very little improvement whatsoever.

TROUP, UK: Could I just add to that particular point? If you further increase the lumbar extension under those conditions, what tends to happen is that the lumbar curve -- the area of the lumbar curve in the back support -- will then press into the lumbar spine; and you will then lose all support. The result, if you increase it further, would be to reintroduce back pain due to local pressure.

BACK PAIN IN GAZELLE AIRCREW

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SUMMARY

The prevalence of backache amongst helicopter aircrew has long been known to be unacceptably high. The introduction of the Gazelle helicopter to UK service has resulted in an apparent increase in this prevalence.

This paper is based on a questionnaire issued to Gazelle aircrew serving in Germany during 1981. The aim was to produce numerical evidence of the prevalence of backache in Gazelle aircrew, to delineate the factors responsible in the aircraft and to make recommendations for re-design.

The major findings of the survey are that 82% of aircrew complained of Gazelle related backache, the taller pilots being worst affected. Flights lasting longer than one hour gave rise to backache in 70% of the subjects. The seat design features considered responsible were the design of the seat cushion, inadequate lumbar support, routing of the shoulder harness and the angle of seat rake.

Since the completion of this survey, a trial of a new Gazelle seat has been carried out. The new design includes an improved seat cushion, inflatable lumbar support, and increased height of the harness take off point from the inertia reel. The results of the initial trial are conclusive in their support for the new seat. These improvements have been incorporated into the design of the Gazelle armoured seat currently under development.

BACKGROUND

Previous studies (1-6) have indicated that aircrew back pain is an important aspect of aircrew health which deserves closer attention. Persistent discomfort causes pre-occupation and distraction and interferes with the performance of complex flying tasks.

The prevalence of backache among aircrew has long been known to be high and is recorded in numerous reports. Since the introduction of the Gazelle helicopter, in the early seventies, there seems to have been an increase in this prevalence amongst UK aircrew. This paper analyses the findings of a questionnaire given to Gazelle aircrew during the Summer of 1981 and describes the seat modifications carried out to improve aircrew comfort.

METHOD

Gazelle aircrew, stationed in Germany, were asked to complete a questionnaire with space for additional comments. The results of the questionnaire are given below. 119 replies were received, of which 89 were from pilots and 30 from aircrew observers. This represents a good response rate of 80%. The multiple choice part of the questionnaire enabled evidence of prevalence, timing and location of backache to be evaluated. Response to questions concerning factors responsible for backache were also analysed. The salient features are discussed. Additional comments were offered by 55% of subjects and consisted mainly of redesign recommendations to minimise discomfort.

RESULTS

Biographical Details

Question 1: Age - Subject age ranged from 20 to 42 years (three declined to answer!).

Question 2: Height - The range of acceptable height for Army aircrew was encompassed (163 to 198 cm) (64 to 78 in).

Question 3: Flying hours - Total hours flown ranged from 40 to 4700 hours with a mean of 1160 hours. Gazelle flying hours ranged from 20 to 2700 hours (mean 588 hours).

Question 4: Current helicopter - 98 were employed flying the Gazelle. The remaining 21 flew Scout or Lynx. 11 flew Scout and/or Lynx as well as Gazelle.

Question 5: "Do you adjust your seat primarily for:"

(a)	Optimum vision	5 (4%)
(b)	Optimum control position	77 (65%)

(c)	A compromise between these	34 (28%)
(d)	Other reasons	3 (3%)

Question 6: "With your seat in the normal position, and sitting in your normal posture, how easily can you reach and fully operate your critical and emergency flying controls?"

3 (2.5%) subjects made no comment.

76 (64%) stated no problems.

8 (7%), all of whom were pilots, had satisfactory control except for the left hand side of the console. This problem showed no predilection for height.

19 (16%) made the point of having to stretch although controls were reachable with the harness locked. With one exception, these were all pilots and the majority were less than 178 cm (70 in) tall.

13 (11%) needed to unlock the harness to reach critical controls. The majority again were under 178 cm (70 in) in height.

Question 7: "Do you find the Gazelle crew seat comfortable?"

92 subjects (77%) found the seat uncomfortable.

Question 8: "How does the Gazelle crew seat compare with others you have flown in?"

(a)	More comfortable	9 (8%)
(b)	About the same	28 (23%)
(c)	Less comfortable	82 (69%)

Seventy answered which crewseat they considered the most comfortable:

(a)	Scout	46 (66%)
(b)	Lynx	19 (27%)
(c)	Gazelle	3 (4%)
(d)	Sioux	2 (3%)

Question 9: "Have you had a previous back injury?"

25 had had a previous back injury of whom only one had osilated non-Gazelle related backache. The remaining 24 all suffered backache flying or after flying Gazelle. 8 had backache flying other aircraft.

Question 10: "Do you get backache?"

Total figures shown are higher than the number sampled as some subjects indicated more than one group.

(a)	No	18 (15%)
(b)	Yes, when flying Gazelle	76 (64%)
(c)	Yes, after flying Gazelle	38 (32%)
(d)	Yes, not related to flying Gazelle	13 (11%)

No relationship was found between the prevalence of Gazelle-related backache and age or hours flown. There was a variation with subject height as shown in Figure 1.

Question 11: "Do you get backache flying other types of aircraft?"

35 subjects (29% of all questioned) had backache in other helicopters. All but 4 of these also had Gazelle-related backache. Scout, Sioux and Lynx were equally incriminated.

Question 12: "If your backache is related to flying Gazelle, when does it occur?"

Answers were as shown below. Some subjects indicated more than one group.

(a)	Not applicable	20 (17%)
(b)	On or after some flights	13 (11%)
(c)	On or after most flights	9 (8%)
(d)	On or after flights lasting more than one hour	68 (57%)
(e)	During or after periods of intensive flying (over 20 hours in last 10 days)	21 (18%)
(f)	During or after high concentration or high workload	18 (15%)

Question 13: "Where does your backache occur?"

Of those with Gazelle related backache, the following answers were obtained. Some indicated more than one site.

(a)	Lower back	73 (61%)
(b)	Mid back	34 (29%)
(c)	Buttocks	28 (24%)
(d)	Shoulders	9 (7%)
(e)	Neck	1 (1%)

Question 14: "What do you think causes your backache in the Gazelle?"

Five gave no answer and 15 answered "Not Applicable" which accounts for all without backache plus 2 others. This was a ranking question: of the 99 who gave a first reason, 89 also gave a second reason: 76 a third reason and 38 a fourth reason. Only 19 gave fifth and sixth reasons and these are not considered in the results.

	Choice (No of answers)				
Reason	1st	2nd	3rd	4th	Total
Shape of back cushion	47	22	7	5	81
Shape of seat	35	27	15	1	78
Routing of shoulder harness	10	18	12	7	47
Angle of rake of seat	2	9	17	4	32
Inadequate seat adjustment	2	6	6	4	18
Position of controls	1	2	7	3	13
Position of seat	0	2	6	4	12
Weak back	1	1	3	6	11
Compliance of seat cushion	1	2	1	3	7
Position of instruments	0	0	2	1	3

Question 15: ADDITIONAL COMMENTS

The following is a summary of additional comments made by respondents:

Comment	No
No comment	54
Recommends use of lumbar support pad	25
Seat produces a 'hunched back'	23
More thigh support needed	10
Seat cushion at fault	8
Backache relieved by lumbar support pad	4
Seat too narrow	4
Gazelle seat is comfortable	1

DISCUSSION OF SURVEY RESULTS

Aircraft seats are often the subject of much criticism in that they are situated in cramped surroundings and are occupied without interruption for much longer periods than domestic or car seats. The nature of the task, which their occupants perform, limits individual movement to adjust position and discomfort, if not frank backache, is a common problem. Backache is usually the result of repeated abnormal strain forcing a structurally normal spine to function at a disadvantage.

Several aspects are worthy of note. The helicopter pilot must adopt a distorted body attitude when operating conventional helicopter controls. Normally, he first adjusts his seat so that operation of the pedals is possible. He then rests his right forearm on his right thigh to enable more precise control of the cyclic stick by the right hand. The left hand then rests on the collective lever which is adjacent to the left hand side of the seat. The left shoulder is forced to drop and the spine is rotated to the left. This classic helicopter pilot position is shown clearly in Fig 2. The normal cruising attitude of the helicopter (4° nose down for the Gazelle) compounds the problem. The upper torso being tipped forward against the restraint provided by the shoulder and lap belts. Many aircrew are also unaware of the correct strapping in procedures.

Incidence of Backache

It was apparent from this review that 99 subjects (82%) had Gazelle-related backache. Whilst this includes 24 with a previous back injury (details of which are not known) it must be assumed that the majority had otherwise normal spines and that their backache was attributable to flying helicopters, the Gazelle in particular.

There did not appear to be any correlation with age of aircrew or the hours flown either totally or restricted to Gazelle. The height of aircrew was undoubtedly a factor influencing backache. The Gazelle seat and cockpit environment seems to favour the range of 162 to 170 cm (64-67 in) and 180 to 185 cm (71-73 in).

Flights lasting longer than one hour gave rise to backache in 70% of subjects. It is assumed that symptoms arose after this critical period and not before. This finding is supported by clinical experience and is probably related to the necessary immobility imposed by the flying task. Problems tend to be greater when workload is long and tedious. Operational workload is high in this aircraft. Gazelle crews in Northern Ireland frequently fly 7 hours a day.

The site of backache correlated well with the theoretical site of spinal stress. 61% had lower backache and 29% mid backache. Buttock ache was felt by 24% and is almost certainly due to loss of compliance of the current seat cushion.

Cause of Backache

Personal opinions of the cause of individual backache provided a useful insight into factors which may be amenable to redesign. The shape of the back cushion was the most popular criticism, being cited by 68% of subjects. The lower back is the area of greatest stress and the site of most postural disorders among aircrew. Lumbar support is needed which the present design of crewseat does not provide. The seat is concave at its base and this deficiency encourages abnormal spinal alignment. Privately acquired lumbar pads used in this seat have helped many and individually moulded fibreglass supports are available through the service to those with longstanding problems.

The overall shape of the Gazelle seat was another popular criticism. Unfortunately, few respondents made specific comment. Particular items worthy of note were its narrowness and consequent protrusion of fixing bolts into the hips. Many complained of protrusion of the front of the seat into the underside of the thighs. This not only caused discomfort, but paraesthesia in some cases. The upright position of the seat was criticised by 32 subjects. This feature again produces abnormal stress upon the lower back as well as undue pressure on the underside of the thighs. Modification by increasing the backward tilt of the seat, together with additional thigh support, may help.

The Gazelle seat has only four positions of fore and aft adjustment. No vertical adjustment is provided. The Gazelle has such excellent visibility that seat position is generally adjusted for optimum control and not for visual reasons (supported by answers to the questions).

Notwithstanding this, some aircrew may tend to have an exaggerated body image and sit too far back on the adjustment. A larger number of horizontal stops, together with vertical adjustment at the front of the seat, would facilitate the attainment of optimum posture.

The routing of the shoulder harness was criticised by 47 subjects, of whom threequarters were 178 cm (70 in) or more in height. The main point was that the release point was set too low on the seat back, thus creating a hunching of the shoulders with subsequent compression of the lower spine.

It is interesting to note that the aircrew questioned in this survey were generally only wearing temperate aircrew equipment assemblies. The requirement to carry body armour, NBC equipment, nigh vision goggles and dinghy back packs in any future conflict can only serve to increase the existing discomfort.

Persistent backache is associated with premature fatigue, irritability, distraction from the task and interference with post-flight relaxation and sleep. It is likely that persistent backache in operational squadron aircrew and instructors could contribute to the level of stress and performance might be impaired. Seat design should allow the occupant to adopt a number of good postural positions whilst discouraging the adoption of a single poor one. Because of the drawbacks inherent in the design of aircrew seats, the enforced sitting posture should be as near perfect as possible. Measures to prevent back strain must aim at elimination of as many as possible of the seat design features which contribute to spinal deformation.

The preferable solution is, of course, the introduction of a totally new helicopter design concept. Adherence to the classic control configuration will, even with a good seat design, result in the continuance of the present problem.

DEVELOPMENT OF A MODIFIED GAZELLE AIRCREW SEAT

The Gazelle is the most numerous helicopter in UK military service, being found in all three services.

The major problems with the current seat, Fig 3, can be summarised as follows.

a. Seat Cushion. The present in service seat cushion can only be described as appalling. Most have been in situ for the life of the aircraft. Pilots are required to report as defective, but this action is rarely taken as the method is subjective and few pilots have experienced the 'feel' of a new cushion to use as a control. The soft seat cushion results in pelvic rotation.

b. The absence of any integral lumbar support coupled with (a) results in the loss of the normal lumbar curve.

c. The low seat back and the shoulder harness take off point cause compression of the torso, especially in subjects with high percentile sitting heights. This factor is compounded by the fact that many aircrew are unaware that the shoulder harness as fitted to the Gazelle is effectively a variable loop passing round the neck. Overtightening of the shoulder harness beyond the point of comfort does not affect the degree of restraint, but merely compresses the torso, exaggerating any undesirable posture already present. This can be seen clearly in Fig 4.

The results of the questionnaire and much anecdotal evidence resulted in a trial being carried out, under the auspices of the RAF Institute of Aviation Medicine, to develop a Gazelle crew seat comfort package. Financial restrictions ruled out a totally new design, so efforts were directed to modifications of the existing seat, cushions and harness assembly.

Trials were carried out on a tri-Service basis involving three types of prototype seat cushion, various lumbar supports and alterations to the inertia reel take off point, which would now be some 5 cm higher than the in-service seat. The results of the trial clearly favoured the combination of an increased harness height, an IAM/RAE designed cushion and a pneumatic lumbar support. The components of this re-design can be seen in Fig 5.

The cushion consists of a front and rear module. Each section comprises two pieces of foam, the upper layer of the rear cushion being T41 contour foam.

The pneumatic lumbar support allows the aircrew to select the optimum adjustment required.

The results of the trial are shown in Table 1. Details of questionnaires commenting on the other cushions and lumbar supports are not included but are held at the IAM.

	COMFORT				
	Much more	Slightly more	Same	Slightly less	Much less
Total assembly	24	7			
Seat cushion	19	16			
Pneumatic lumbar support	19	9	9		
Trial seat	21	6	1		

Table 1. Assessment of IAM/RAE Comfort Package

The Gazelle seat comfort package is now entering service in large numbers and the improvements offered have also been included in the design of the Gazelle armoured seat (Fig 6), which is to be fitted to all Army Air Corps Gazelles.

Clinical Aspects

The clinical care of aircrew must not be forgotten and it is considered that all backache complaints must be reviewed by a Medical Officer so that appropriate action can be taken. The algorithm shown below (Fig 7) is followed by UK Army Specialists in Aviation Medicine.

Few aircrew ever see their Medical Officer concerning their back problems. Most consider it an inevitable accompaniment of their chosen career and are also chary of the possibility that they may be grounded temporarily, or in some cases, permanently. Of UK Army aircrew very few indeed have gone as far as hospitalisation, though many have benefited from general advice and in more severe cases, the issue of a moulded fibreglass lumbar support.

In the past many aircrew who were outside the prescribed anthropometric limits have been allowed to become helicopter pilots. Some of these, who are in excess of the 99 percentile, have had severe lumbar problems, especially in the Gazelle where sitting height limitations are critical.

CONCLUSIONS

1. The introduction of the Gazelle has resulted in a high prevalence of back pain being reported by helicopter aircrew.

2. Comparatively simple modifications to the seat design have resulted in a useful improvement in aircrew comfort.

3. Although seat reldesign can help alleviate the discomfort, new cockpit configurations are essential if the problem of persistent back pain is to be erradicated.

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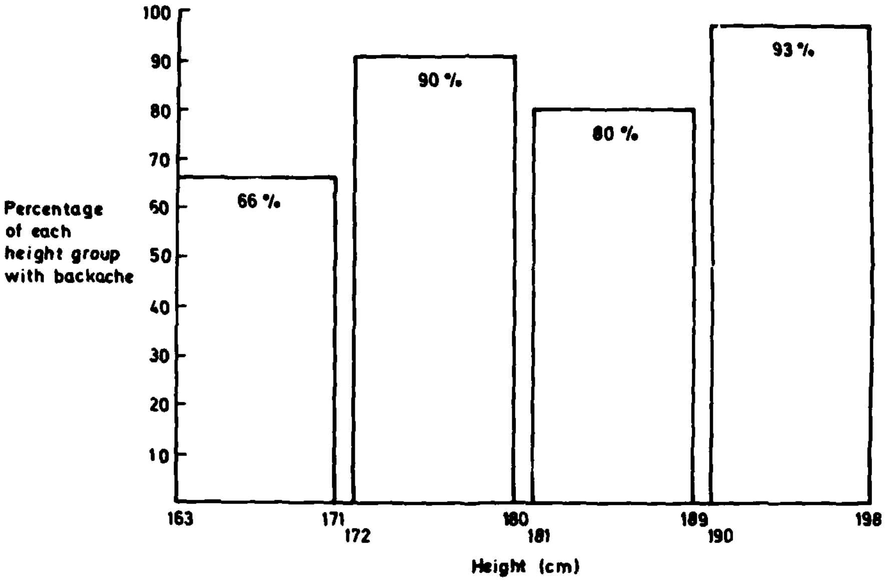

FIG 1. Percentage of Aircrew Suffering Backache as a function of aircrew height.

FIG 2. The Classical Helicopter Position

FIG 3. The current Gazelle seat is shown on the left. The redesigned seat is on the right.

FIG 4. Subject with Incorrectly Tensioned Shoulder Harness Demonstrating Compression of the Torso.

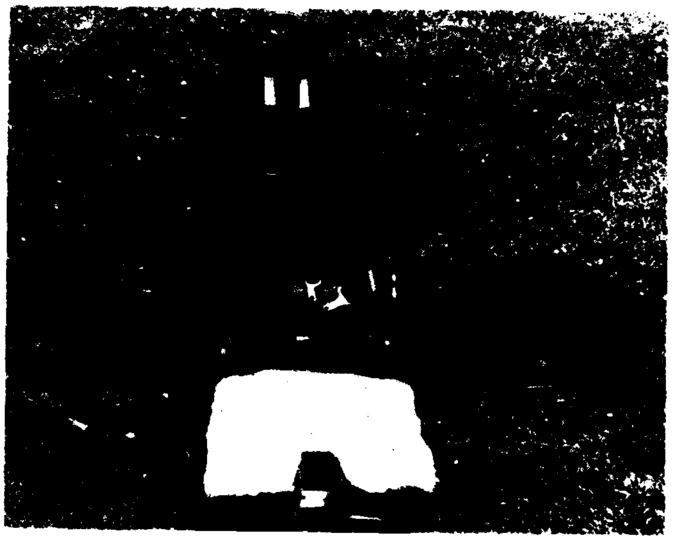

FIG 5. Redesigned Gazelle Crew Seat Showing New Cushion, Pneumatic Lumbar Support (on left) and Increased Take Off Point for Shoulder Harness.

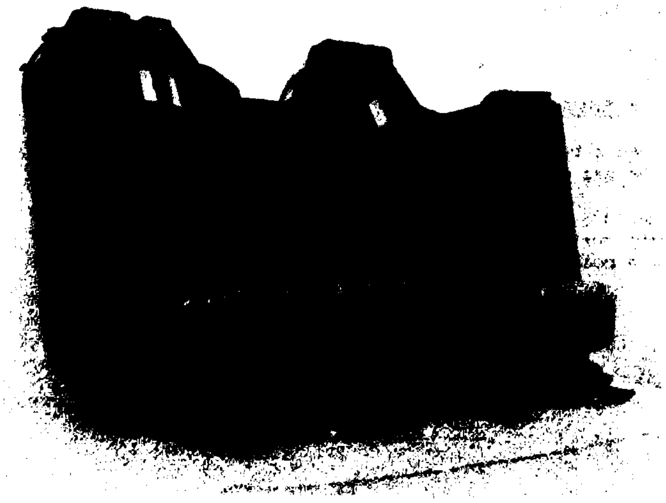

FIG 6. Prototype Gazelle Armoured Crewseats.

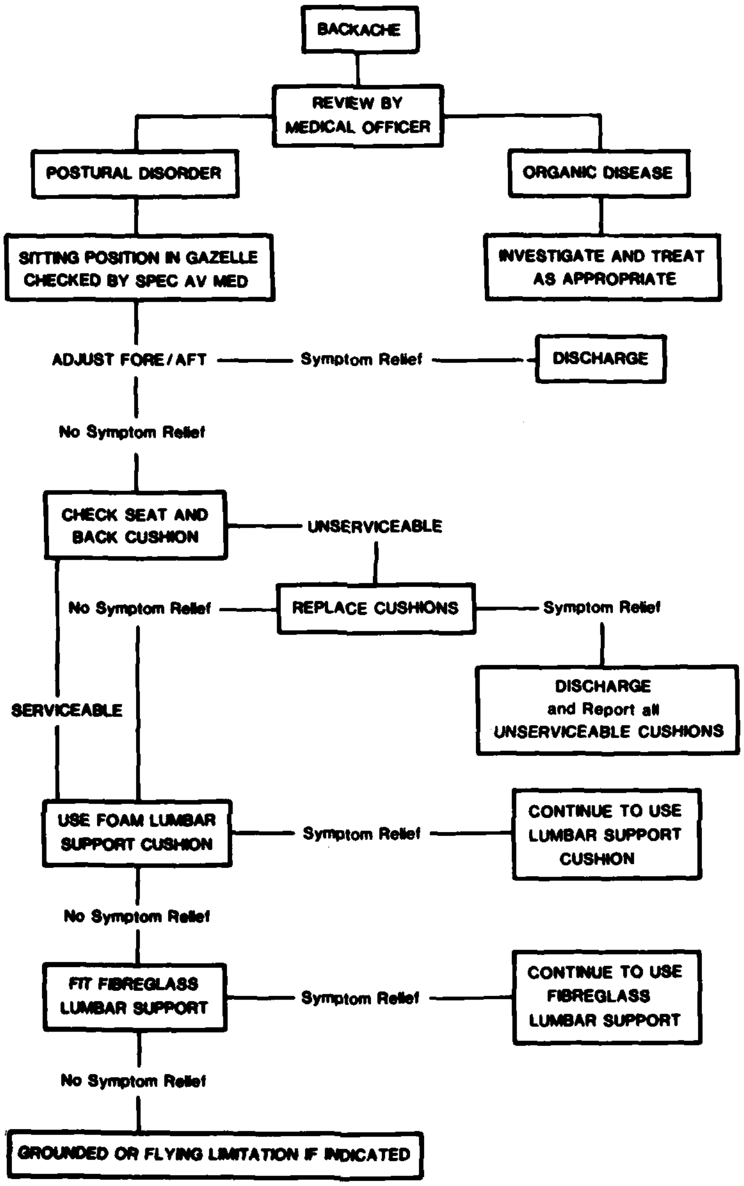

FIG 7. Algorithm demonstrating treatment of aircrew suffering from backache.

DISCUSSION

BOWDEN, CA: Is it true that a pilot can use a back rest while in control of the aircraft, or is it possible that the helicopter hunch prevents the use of a back rest?

BRAITHWAITE, UK: From personal experience, it is possible to use back rests, of varying kinds while still maintaining precise, adequate and good control of the helicopter. It certainly is not prevented by the helicopter hunch; it improves one's posture.

SEAT ISOLATION SYSTEM

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SUMMARY

Sustained low-frequency vibrations in helicopters, combined with poor posture imposed by control configuration, can affect the health and performance of aircrew. Vibration can adversely affect visual acuity, induce stress, lower fatigue limits and cause spinal or kidney damage. These effects may occur even in helicopter simulators. Some air vehicles expose the occupants to levels of vibration and shock which exceed the comfort or fatigue decreased proficiency criteria established by the International Standards Organization (ISO 2631) and, in some cases, exceed the exposure limits of that standard. The attenuation of vibration is recognized as a critical problem in the design of future helicopters, and new (sidearm) control configurations under development may permit better posture. However, it is certain that these problems will persist and that they exist in the current generation of helicopters. Conventional approaches isolate a pilot with a seat suspension which attenuates the dominant (vertical) axis of vibration. Such seats are typically passive, relying on a system of springs and dampers to attenuate the most critical combinations of expected frequency and g level.

The bulk of such seats often precludes retrofitting them to existing air vehicles. Active shock/vibration isolation seats which offer advantages in terms of attenuation and frequency response have been proposed but no successful system has been developed to date. Some flight simulators employ g-seats to simulate g-forces acting on the pilot in high-performance aircraft. The expertise gained in developing, testing, and manufacturing the g-seat provides an ideal basis for developing an active antivibration seat. The frequency range of the g-seat includes the critical band of damaging and fatiguing vibrations in the vertical axis. Laboratory trials have demonstrated that the seat can attenuate the vibration to which the pilot is exposed. Concurrently, development of a displacement multi-axis hand controller for helicopter application is under way. Successful flight tests have been conducted with this unit configured as a side arm controller, permitting pilots to maintain an upright posture. Thispaper describes an approach and methodology for development of an active antivibration seat within the context of an integrated cockpit seat/control system. The intent is to achieve a high level of crew safety and comfort in concert with improved control performance.

1. INTRODUCTION

Aircraft vibrations induce fatigue and discomfort to the passengers and crew. Helicopters are particularly susceptible to this problem since vibrations tend to occur at lower frequencies than in fixed-wing aircraft. The vibration may be self-excited or externally excited. Examples of self-excited vibrations are ground resonance (in which blade lag motion is coupled with a translational oscillation of the motor hub) and blade flutter (which involves the coupling of blade flexure and twist with aerodynamic loads). Self-excited modes of vibration can build up so rapidly that they destroy the helicopter within a few seconds, hence pilot proficiency in a dynamically degrading environment is critical. Externally excited vibrations typically arise from aerodynamic loads on the rotors, engine and gearbox vibration, and aerodynamic loading on the airframe. The content of the helicopter vibration spectrum varies with the location at which it is measured withing the helicopter as well as the type of helicopter under investigation[1]. In addition, there is variance in the spectra of helicopters of the same type[2].

However, the vibrations of greatest amplitude and of most concern fall within a limited (less than 20 Hz) range for all helicopters. These vibrations are associated with the main rotor blade and system passing frequency: for a two bladed rotor at 360 RPM they would be of the order of 6 Hz rotor frequency and 12 Hz blade passing frequency (eg. Bell Jetranger), and for a five bladed rotor at 206 RPM on the order of 3.3 Hz rotor and 16.7 Hz blade passing frequency (eg. Sikorsky S-61). The amplitude of these vibrations increases with the aeordynamic load on the rotor system (eg. hover or high speed) and are most severe during transient high power applications such as hard turns or the final phase of an autorotation.

The problems related to main rotor beat frequency are exacerbated by the fact that the human body has resonant frequencies in the range of 4-8 Hz due to: coupling of vertical movement of the rib cage and shoulders relative to the hips and vertical movement of the contents of the abdominal cavity[3]. Movements at the shoulder may be amplified to 4 times those at the pelvis[4]. Weight, muscle tone, and especially posture of the pilot, may change the transmissivity of vibration to upper body members by a factor of six[5]. There is a tendency to shift posture to move natural resonance frequencies away from the driving frequency. For example, in the 4 Hz region, erect seating posture reduces head transmission.

However this shift is not straightforward, as increased contact with the back rest may transmit more vibration in the 12-20 Hz range - this hits a head resonant mode which may degrade visual performance. Use of posture shifts in helicopters is further limited by the characteristic control configuration and dynamic instability.[26]

Relative to fixed wing aircraft, helicopters are unstable flying platforms and require considerably more active pilot control. Poor ergonomic design of flight controls in typical helicopters forces many pilots to "hunch" over the cyclic stick to obtain precise control as well as to lean forward and to the left to use the lower range of the collective. In effect then, helicopter flight controls impose poor posture on the pilot, and the necessity to operate the controls continuously makes it difficult to alter posture beyond a limited range without affecting the conditions of flight. The poor posture itself may induce fatigue and discomfort, but perhaps more seriously, it greatly increases the pilot's vulnerability to the effects of vibration. The compressive load on the spinal discs of a slouching seated man may be as much as double that in standing, and the disc stiffness in compression increases as the force and rate of application of force to the spinal column increases[6]. This passes shock loads directly to the vertabrae.

Prolonged exposure to low-frequency large-amplitude whole-body vibration causes degenerative physiological symptoms and degradation in responding to stimuli pertinent to human safety and efficiency[7]. Several investigations have been conducted into the physiological effects of vibration in the helicopter environment with reported incidence of back pain ranging from 21% to 95% of pilots examined. The vibration-induced symptoms range from motion sickness[8] to permanent damage to the spine and supporting tissue structure[9-11]. Other investigators[12-14] have concluded that low-frequency vibration may affect compensatory tracking ability, reaction time, physiological responses, and emotional reactions. With respect to motor control per se, greatest effects appear to occur in the primary resonant frequency range about 4 Hz, with the effects including fatique, loss of concentration, and loss of kinesthetic sensation (numbing)[15,16]. With respect to visual losses, it may be that vibration amplitudes in the 12-20 Hz range are typically not sufficient to induce visual blur. Amplitude and the lower resonant range (4-8 Hz) however, may be sufficient, especially if posture is poor (above 6 Hz) or if effectiveness of eye/head compensation is degraded due to fatique (below 6 Hz)[15,16].

To summarize, poor posture combined with excessive vibration levels in helicopters may result in crew fatigue, crew discomfort, degradation of performance, and physiological degeneration. The exact nature of the interrelationship between these two factors and the tradeoffs therein, for example postural shifts, are not fully understood. A standard relating vibration exposure to health comfort and performance has been established by the International Standards Organization[17], but has not been fully validated and is not universally accepted[18-20]. What is clear however, is that the problem exists, that it is serious, and that remedial measures must be taken.

2. SOLUTIONS

Our goal is to reduce the negative effects of poor posture and vibration upon aircrew. A number of simple measures readily come to mind. One contribution may be to ensure that aircrew are less vulnerable by selecting for absolute absence of back problems. This is probably not viable because: back problems are very common and easily concealed, and the pilot selection procedure is already restrictive and expensive. Further, given the environment, those who enter helicopters without back ailments are likely to develop them. Encouraging pilots to participate in physical fitness programs to improve muscle tone would be a positive step.

Another contribution would be to substantially reduce helicopter airframe vibration. Certainly this is being addressed in new helicopter designs. However, given the basic characteristic of helicopter aerodynamics, it is unreasonable to assume that vibration may be totally eliminated and there remain thousands of contemporary machines with existing vibration characteristics.

A further contribution would be to augment the stability of helicopter flight controls and permit improved pilot posture by implementing fly-by-wire control systems with sidearm control units. While development of fly-by-wire control systems for helicopters has not been driven historically by ergonomic consideration[21], these considerations are a primary concern in current development of displacement sidearm controllers[22]. This development permits remediation of two major problems at once, since use of the sidearm controller permits fully supported upright posture, and implementation of fly-by-wire augmentation improves stability to the point that pilots may easily shift posture without substantially affecting aircraft control.

A final contribution is to reduce the vibration impinging upon the pilot through his seat, since even with improved posture, the shock transmitted to the spine and effects of vibration upon performance remain serious problems. The hardware section of this paper describes considerations in the design of an active anti-vibration seat.

3. PASSIVE VERSUS ACTIVE SEAT SUSPENSION

There are fundamental limitations inherent in the conventional helicopter seat which are incompatible with the requirements of aircrew health, comfort and performance. The conventional seat typically utilizes foam rubber or taut fabric to support the occupant as well as isolate him from the vibration present in the immediate environment. The basic limitation is that the static deflection varies with the inverse square of the system's natural frequency[23]. In addition, pilot eye level and dynamics vary with weight. To overcome the static deflection problem, the materials used in conventional seats typically have nonlinear force-deflection characteristics. Unfortunately, operation in the nonlinear deflection range makes the seat behave as a much stiffer suspension system, resulting in degradation of the vibration isolation characteristics[24], particularly at large amplitudes.

In recent years active seat suspensions have been developed for use in offroad vehicles[23-29]. Active seats are servomechanisms comprised of excitation and/or response sensors, signal processors, and actuators. The sensors provide signals proportional to excitation or response quantities.

The signal processor manipulates sensor signals to create a command signal. The actuators then apply forces or induce motion in accordance with the command signal.

A variety of excitation and response sensors can be utilized to provide feedback signals in the closed-loop configuration of an active seat. Feedback signals can be developed that are a function of jerk, acceleration, velocity, displacement, differential pressure, or force. The signal processor may consist of an active network that performs amplication, and compensation functions. The principal advantages of an active seat are twofold:

- Active seats continually modulate the flow of energy to the active seat elements. Passive seats can only dissipate, temporarily store, and return energy. Hence, in an active seat, forces can be generated which do not depend on enegy previously stored or the duration of operation.

- By using appropriate measurement and signal processing devices, an active seat can generate forces which are a function of several variables, some of which can be remotely measured. Passive seats are restricted to generating forces only in response to local relative motion.

The performance advantages of an active seat over a conventional seat can be defined using a lumped parameter approach[30], an approximation based on the assumption that masses, springs and dumpers can be isolated and concentrated at a single point. The nondimensional acceleration transfer functions of the conventional seat (for various material damping ratios) and the optimal active seat are plotted in Figure 1 against nondimensional frequency. At low frequency, the active and passive seats have equal acceleration gains. At higher frequencies, the conventional seat has a much higher acceleration gain while the active seat retains a unity nondimensional gain. In practical terms, the conventional seat amplifies high-frequency vibration because the damping material in the seat becomes dynamically hard. If the damping in the conventional seat is reduced, the high-frequency amplification is also reduced. However, for damping ratios less that 0.707, the acceleration gain is increased at unity nondimensional frequency. In passive suspension design, a tradeoff is usually made between low and high frequency performances[31], a compromise avoided by using active seats.

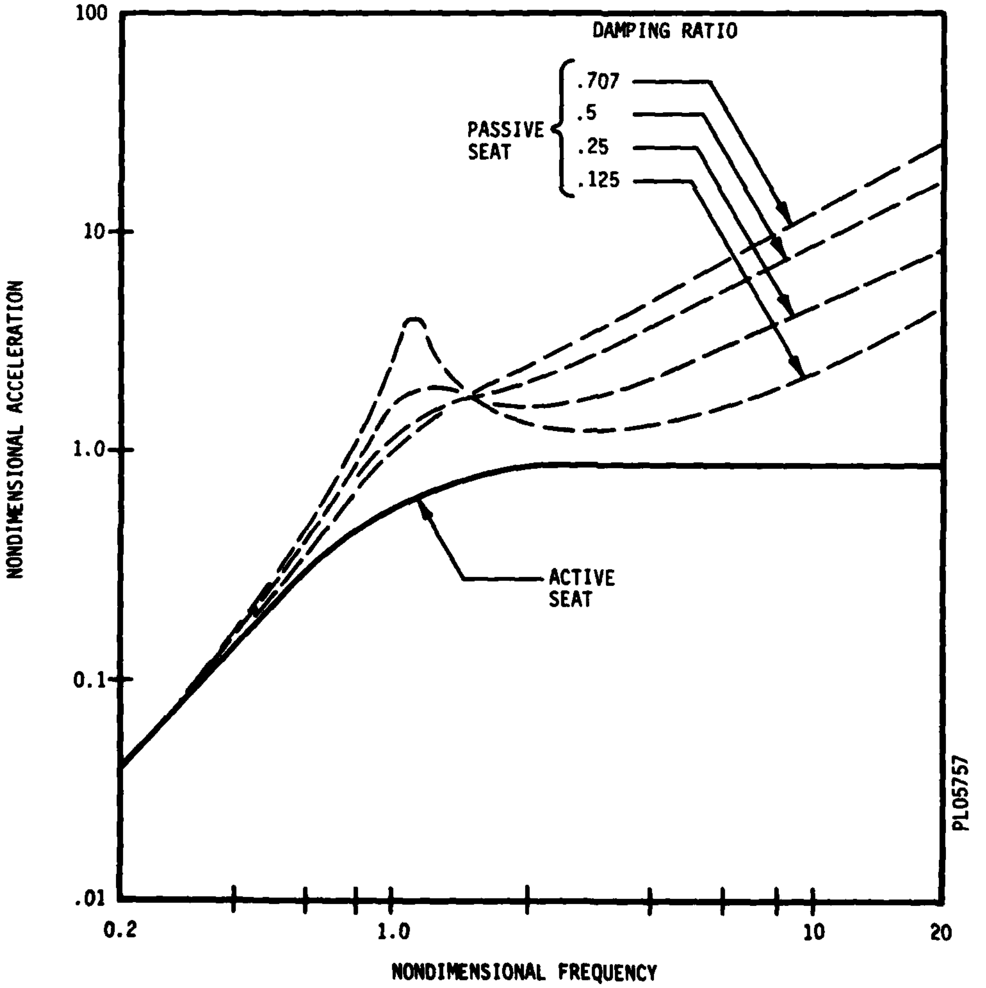

Figure 1

Nondimensional acceleration transfer functions versus nondimensional frequency

4. THE G-SEAT AS A MOTION CUING DEVICE

In center-thrust high-performance aircraft, the pilot experiences large and sustained accelerations. He senses these accelerations through his inner ear (or vestibular system) where the otoliths sense linear acceleration, and the semicircular canals sense rotational accelerations. In addition, he responds to somatic cues through the haptic sensing system, i.e., through interaction with the seat. During upward acceleration he feels himself sink into the seat and the seat feels hard under him. Accelerating downward, he feels himself lifted from the seat and constrained by the safety harness. The sensations of these accelerations (or g's) can be simulated using a seat with inflatable cushions in conjunction with a servo-driven safety harness.

The design of the antivibration seat is based on the successful g-seat used on German Tornado and Canadian CF-18 simulators. The g-seat (shown in Figure 2) is an oil-over-air mechanism consisting of two matrices of four cushions, one on the seat pan and one on the seat back. Each motion cell is connected to an individual air bellows forming a closed loop system. The air bellows are activated via a hydraulic actuator. A linear position transducer and pressure transducer provide the necessary feedback. A solenoid valve permits the closed-loop system to be charged as required. The motion cells are activated by command signals from the system software in accordance with the simulated aircraft characteristics. By providing a matrix of inflatable cells in the seat pan and seat back, effective acceleration cues are provided in all six degrees of freedom as shown in Figure 3 and 4. The air pressure in the motion cells is calibrated to approximate the -1g to 7g accelerations experienced throughout the flight envelope. Buffet and vibration effects are blended with sustained g-cues. The system provides vibrating cues between frequencies of 0.25 to 20 Hz, at amplituded of up to 0.7 cm. From 3 to 20 Hz, the buffet spectrum duplicates that of the simulated aircraft for all flight conditions.

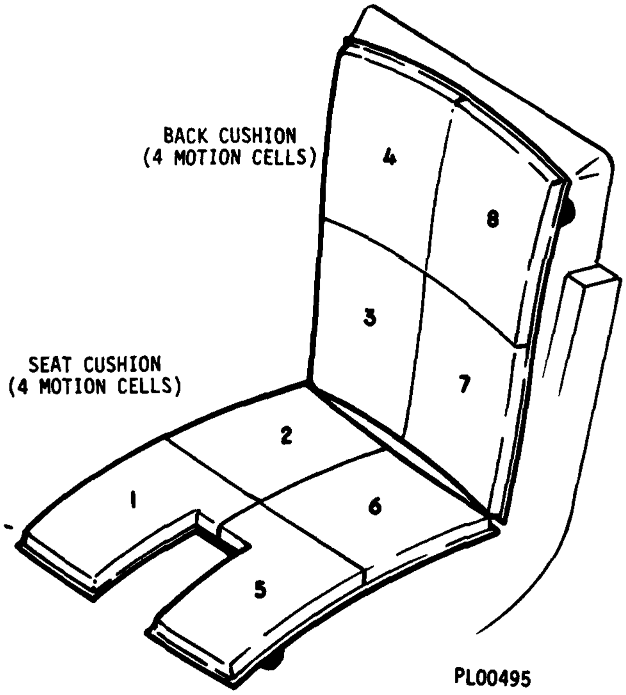

Figure 2

G-seat cell layout

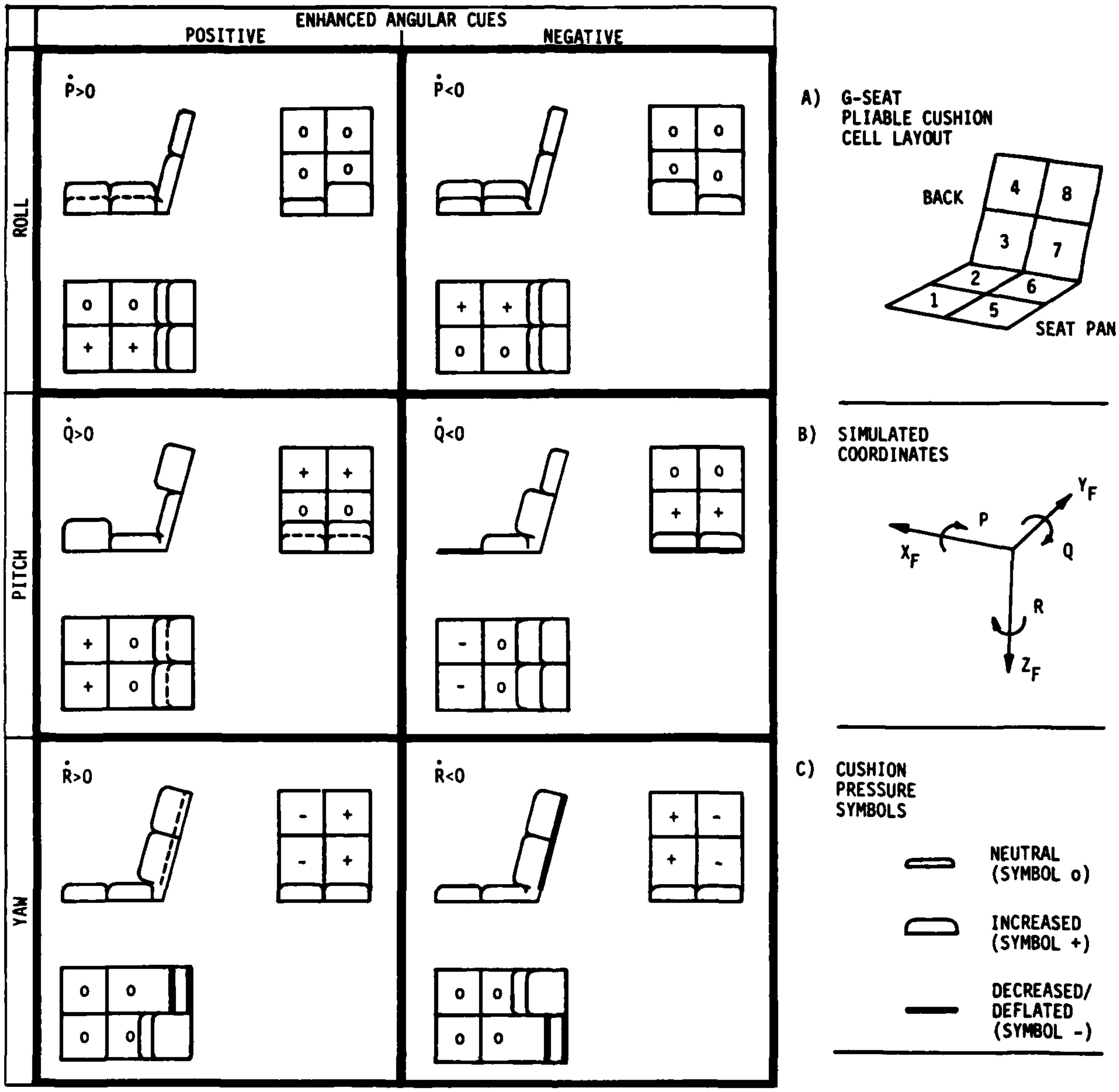

Figure 3

Angular acceleration cuing diagram

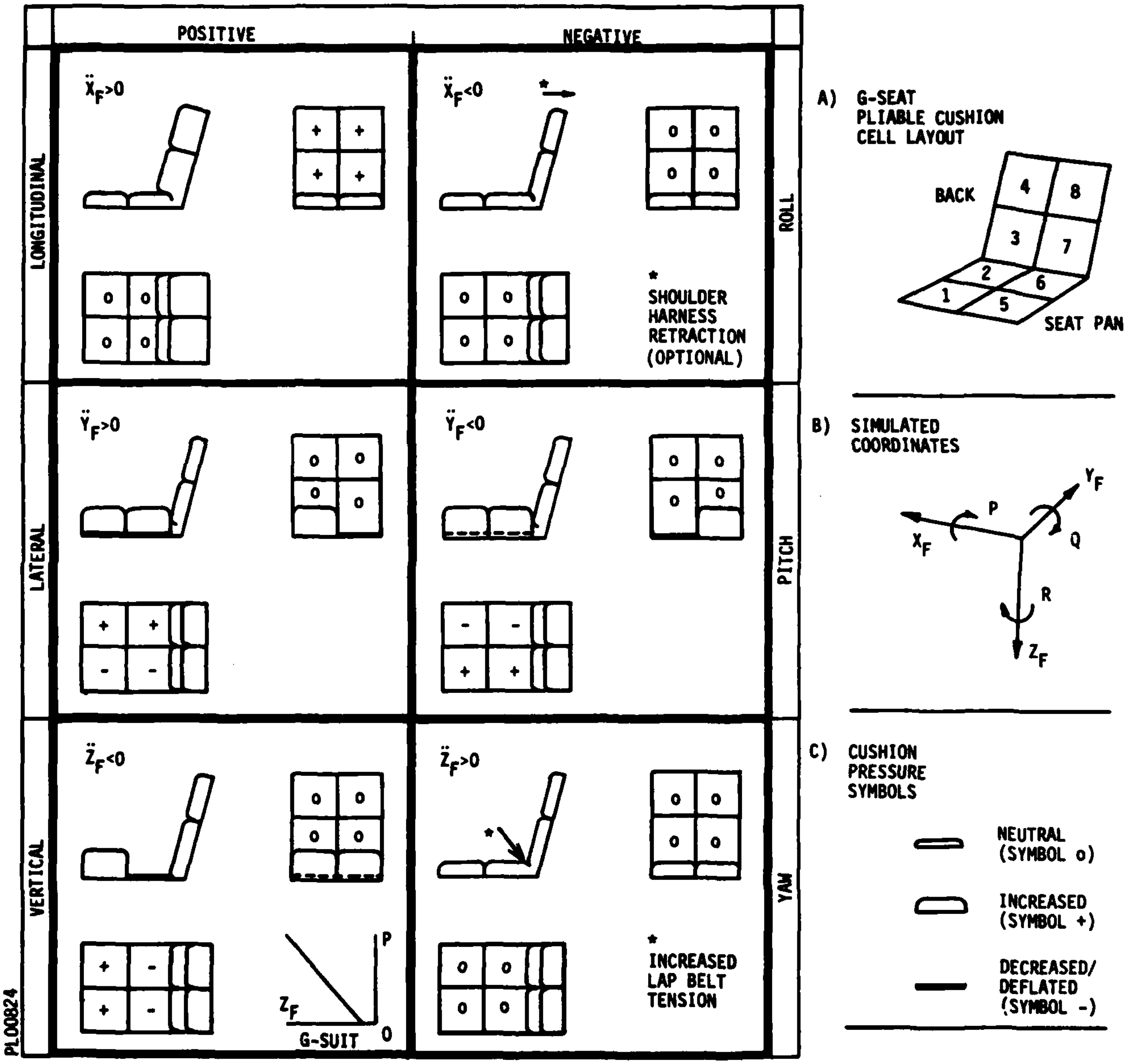

Figure 4

Linear acceleration cuing diagram

5. THE G-SEAT AS AN ANTI-VIBRATION DEVICE

The expertise gained in developing, testing, and manufacturing the g-seat provides an ideal basis for developing the concept of an antivibration active seat. The g-seat can effectively work in a reverse mode. The motion sensor inputs replace the software-generated motion cues, attenuating the vibration to which the seat is exposed.

Initial tests have been run using a constant-pressure control algorithm. The seat automatically adjusts to compensate for pilot weight, bringing it to its operational neutral point. The vibration causes the pilot to either rise or sink on the seat, creating a positive or negative pressure signal which is then fed into a summing amplifier. The amplifier output drives the hydraulic actuators which in turn cause the bellows to either deflate or inflate the active seat, thus maintaining the seat and pilot at the neutral position. Initial tests indicate good isolation in the 3- to 8-Hz range, however, they represent only the starting point of the antivibration seat development program.

The overall objective of a current development program is to design, construct, and evaluate an antivibration seat cushion which can be retrofitted in the CH-147 Chinook helicopter. The adaptive control capabilities of the seat cushion make it suitable for retrofit in a variety of land and air vehicles, with minimum changes to the configuration of the pilot or driver compartment.

At present, the project is reaching the final stages of prototype cushion and control system construction. During the next few months, development and validation trials will be conducted using in-house motion base facilities. The trials will identify the attenuation characteristics of the seat using measures of acceleration transmissibility at the seat-to-occupant interface and other representative points such as hip, upper torso, and head. The trials will initially be conducted using anthropomorphic dummies. The initial trials will study the attenuation characteristic of the prototype seat at frequencies from 1 to 40 Hz, and acceleration levels up to the exposure limit criteria of ISO 2631[17], using sinusoidal inputs. Once an approval procedure has been followed, the trials will be repeated using human subjects representing the size and weight range of Canadian Forces personnel. Subsequent trials will use frequency spectra input and will incorporate pitch acceleration to investigate differential control of the individual air bellows.

In parallel with the seat project a collaborative program between CAE and the National Aeronautical Establishment (NAE) Canada has been underway for the last two years. The primary objective of this program has been development and evaluation of multi-axis controllers as side arm control devices[22]. Experience in the program has indicated that controller position, armrest and seat configuration, and pilot posture are all critical components of performance and acceptability of a sidearm controller. Likewise, effects upon visual and motor control performance are critical parameters in the development of an anti-vibration seat. The intent then, is to develop both the seat and controller systems in an integrated fashion, with each of these systems acting as a testbed for the other in the laboratory. Planning for integrated flight testing of the systems has begun.

6. CONCLUSION

Rationale for improvement of pilot seating arrangements in helicopters has been provided. A side-arm controller design based upon ergonomic principles has been developed. A viable approach and methodology for development of an antivibration seat to isolate helicopter pilots from vibration has been established. The limitations of the conventional passive helicopter seat were contrasted against the performance potential inherent in an active antivibration seat.

The high-performance simulation hardware on which the antivibration seat concept is based was then presented along with a description of the development plan. Further development of an integrated seating/control configuration intended to improve pilot performance, safety and comfort by improving posture, flexibility and vibration isolation is indicated.

7. ACKNOWLEDGEMENTS

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DISCUSSION

KLAVENESS, NO: Has your so-called active seat been tested for crashworthiness?

VAN VLIET, CA: At this point, it is just a prototype; but, of course, crashworthiness will be one of the qualifiers, as would cold temperature operation, and as would many other flightworthiness factors from flight acceptance trials.

KLAVENESS, NO: Is there a collapsible part of the construction?

VAN VLIET, CA: There are a number of safety interlocks in the design, similar to the ones that we use on our motion base. In fifteen years of operation with our motion bases, we have never had a catastrophic failure.

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14. Abstract

These Proceedings include the 29 papers and ensuing discussions from the Specialists' Meeting sponsored by the AGARD Aerospace Medical Panel held in Pozzuoli (Naples), Italy, from October 8 to 10, 1985.

Backache and back discomfort are serious economic and operational problems in aerospace environments. The objective of the Meeting was to bring military and civilian specialists together to discuss modern ways and means of alleviating back problems in the cockpit. The papers addressed both the seating posture and the vibrational environment as contributory factors. Other topics addressed and discussed included the conditions of the spine which predispose individuals to backache, methods for evaluating and predicting back pain, "back-school" programmes for the prevention and treatment of recurrent back pain, and strategies for reducing backache in current and advanced cockpit environments.

These Proceedings will be of interest to those involved in the design of military ground vehicles and aircraft, and those concerned with the health and effective use of aircrew in flight operations.

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