OVERVIEW OF THE NAVAIR SPINAL INJURY MITIGATION PROGRAM

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ABSTRACT

In order to enhance flight performance, numerous Naval and joint DoD development programs feature head-supported devices (HSD) for fixed and rotary wing aircraft, e.g. night vision goggles and displays. However, wearing these systems during long duration operations or while exposed to repeated shock, impact, ejection, and crash increases the risk of spinal injury. Factors that affect injury tolerance include the additional weight, which typically pitches the head forward, age, gender, work/rest cycle, cervical orientation, and behavior. Limited applicable risk criteria exist due to specific gaps in our knowledge of spinal injury in aerospace environments. Current injury criteria are principally based on automotive crash data using individuals without headgear. The Office of Naval Research is sponsoring a multidisciplinary effort led by NAVAIR to quantitatively determine the risk of injury through the development of an anatomically based parameterized probabilistic spinal injury prediction model. This effort includes conducting a series of studies to fill those knowledge gaps and apply the data to build a validated model that accounts for gender, size, and loading factors. New techniques have also been developed to quantify parachute opening shock loads and determine the limits of dynamic neck strength and endurance. By applying these tools, neck injury mitigation devices have been prototyped.

INTRODUCTION

Injury associated with maneuvering acceleration

Aircrew flying high performance aircraft are repeatedly exposed to G levels and high G-onset rates associated with aerial combat maneuvers or air-to-ground ordnance delivery. These acceleration levels affect the ability of the cervical spine to endure the stresses and strains induced by this loading. In particular, head rotation during +Gz stress loads the cervical spine while its articulating facets are not properly aligned. Under these conditions, injury ranging from muscle strain to vertebral fracture can occur. In addition, head mounted equipment increases the neck borne weight, which leads to increased loading and neck muscle fatigue, particularly if the equipment pitches the combined head / helmet CG forward. Muscular fatigue becomes a greater factor given the increased length in operational missions for tactical and rotary wing aircrew. Several survey and retrospective studies conducted in the 1980s attempted to quantify the incidence of neck injury in USN, USAF, and European Air Forces aircrew[2,7-9]. A 1988 survey of 66 F/A-18 pilots indicated that 79% experienced neck pain and, in 56% of those, the pain interfered with present and future missions and 17% were removed from flight status[10]. The final report of a NATO Research and Technology Organization Technology Watch[3] on the musculoskeletal and vestibular effects of long term repeated exposure to sustained high-G indicated that there is a high rate of injury to soft tissues of the necks of fighter pilots due to repeated G exposure and that the cumulative effects of these exposures over time are unknown. Evidence further suggests that neck injury is associated with exposures of +4 Gz and above. (Note that new attack helicopters can achieve +4 Gz and helicopter pilots typically wear heavier headgear than tactical aircrew.) There is evidence that when exposures to +Gz stress are unexpected, injuries can occur at levels as low as +2 Gz[6]. To offset these injuries, lighter weight helmets were

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **OCT 2005**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Overview of the NAVAIR Spinal Injury Mitigation Program**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **NAVAIR Human Systems Department Patuxent River, MD**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

Published in the Proceedings of the Forty Third Annual SAFE Association Symposium, Held in the Salt Lake City, Utah, October 24-26, 2005. SAFE Assocation, Post Office Box 130, Creswell, OR 97426-0130. http://www.safeassociation.org

14. ABSTRACT

15. SUBJECT TERMS

Safe

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

introduced in the 1980's. However, to increase combat effectiveness, the current and projected trend is to use helmet mounted devices (HMD) to improve weapons targeting, night vision, and provide tactical information while allowing aircrew to maintain vision directed out of the cockpit. These devices add overall weight and typically push the helmet/head CG forward, increasing the natural tendency of the head to pitch forward, thereby increasing the injury risk under both maneuvering and ejection acceleration loads.

However, quantitative data concerning the load and moment tolerance limits for neck flexion, extension, and rotation under these operational conditions is poorly understood - with or without HMD. Studies have indicated that most in-flight neck injuries occur during aerial combat maneuvers when pilots move their heads while pulling G's, are in the check-six position, or when an NFO or RIO is taken unaware when the pilot executes a high-G maneuver[1,2,10,18,19].

Additionally, since this problem is related to strength and body position, there is an increased risk for female aviators. Most of the published strength literature focuses on the abilities of females to perform tasks that involve the upper body and lower extremities[20]. In 1976, a review of nine separate studies was conducted by Laubach[11] to determine if the oft-quoted maxim that the general muscular strength of females was 2/3 that of men was true. His most significant finding was that while that percentage was reasonable, females demonstrated an extremely wide range of strength capabilities. Foust, *et al*[5] found that while males typically had stronger neck flexor and extensor muscles regardless of age, females tended to have a larger range of motion and a somewhat faster reflex reaction time. In a study by Shender and Heffner[21], it was shown that small stature females could support balanced added head weight up to +6 Gz, but had difficulties with horizontal acceleration (+/-Gx).

Injury associated with ejection and crash

Mishap injuries during repeated impact, ejection and crash are the result of high loading to the body, particularly to the spinal column. In a report on injury occurrence for Naval helicopter occupants, out of 455 recorded injuries, 20% were spinal (7.9% in the neck and 12.1% in the lower back)[4]. The minor injuries are sprains and strains while the major injuries are wedge and burst compression fractures with accompanying ligament damage of primarily the lower cervical vertebrae[18]. Some cervical distractions with accompanying ligament damage of predominantly the upper cervical vertebrae have also been noted[18]. With the introduction of head mounted systems, the potential for neck injury will increase due to the added head-borne weight. Spinal loading for females and small aircrew resulting in injury has not been identified and there are no available validated criteria that allow quantitative assessment of the probability of injury risk for a particular injury severity. The criteria that do exist are based primarily on scaled male data only. While all possible injury mechanisms cannot be verified through measurement, the data support that there are many injury mechanisms that are not fully understood.

Historically, injury criteria for crash loading and ejection have been based on the average size male, typically referring to the Mertz and Patrick[14] automotive study of 1971, which did not include exposures to +Gz stress. Testing using live subjects has established pain thresholds that are far below injury levels. As a result the operational systems (*e.g.*, ejection and crashworthy seating) are designed for a level of risk that brackets the 50th percentile male. The initial data indicates that there are differences in the vertebral structures and load bearing capabilities of the equivalent size male and female (Whitley *et al.*[23]). This places the female aircrew at an increased risk of injury or fatality for the same ejection / impact loads. Furthermore, human tolerance data are obtained from elderly specimens (more than 65 years of age). Clear distinctions between male and female genders with regard to tolerance and mechanisms of injury are lacking. There are indications that there is a relationship between loading rates, age and gender for compressive loads[17].

Ejection at high airspeeds is a highly chaotic event that can be characterized by several main phases. Each of these phases has inherent risk, and is capable of resulting in injury to the aviator. Parachute opening at high airspeeds is extremely hazardous because of random orientation at the time of deployment and lateral loading combined with the potential for high loads transmitted to the neck. Parachute opening shock results in an abrupt deceleration of the body that occurs when the aviator's personal parachute achieves full inflation. Several variables account for peak acceleration, including aircrew mass, barometric and dynamic pressures, recovery parachute type, drag area, and opening aids (such as spreader guns and reefing). Depending upon the initial position of the body, the deceleration and angular acceleration may be aggravated as the body is twisted and snatched into alignment with the parachute's opening vector.

The NAVAIR spinal model, under development by an internationally recognized team of biomechanical research and injury modeling specialists, will provide the means to predict soft and hard musculoskeletal tissue injury ranging from mild to catastrophic. It accounts for differences in applied force in both magnitude and direction. Relevant gender effects are included since it has been developed using both male and female data. Differences in anthropometric size are accommodated through a parameterized modeling technique. The probabilistic nature of the model allows for valid predictions that produce a distributed range of outcomes based upon a normalized dataset that can be quantified.

The initial focus of this effort, funded by the US Office of Naval Research since 2002, has been on the neck, since it is the most vulnerable and least understood component of the spine. This paper will report on the progress of this effort. However, in 2005, data collection has begun to expand the cervical model to a complete spine. When completed, questions about injury tolerance to repeated impact (fast boats and rough terrain vehicles) and effects of high-weight load carriage can also be addressed by a single integrated modeling approach.

METHODS

The spinal injury program was created to quantitatively determine the risk of injury (1) to the human spine resulting from acceleration exposures during maneuvering flight and (2) from multi-axial spinal injury during repeated shock, high speed ejection, and crash. The goal is to comprehensively define spinal injury thresholds for males and females and guidelines for HMD development, head borne protection, and protective restraint systems (*e.g.*, crashworthy seating, ejection seat system design) that accommodate the expanded Naval population. The approach is to (1) define the mechanical characteristics of the cervical vertebrae, discs, ligaments, and muscles; (2) develop an anatomically based parameterized probabilistic spinal injury prediction model; (3) define the neck injury risk to small females during exposure to all types of acceleration stress; (4) determine the effects of head-borne weight and CG on injury risk; and (5) develop technologies that mitigate injury during flight and ejection/crash. This effort is an integral part of Defense Technology Objective JE.22 (Neck Protection with Advanced Helmet and Vehicle Systems).

APPROACH

MECHANICAL PROPERTIES:

In order to develop the cervical spine model, the mechanical and geometric properties of the hard and soft tissues of the cervical spine must be determined using specimens that represent the size and age range of the Naval population. These data were obtained by the Medical College of Wisconsin and the University of Virginia Center for Applied Biomechanics. Geometric and mechanical tissue properties are determined by (1) quantitative computer tomography (QCT, providing geometric and bone mineral density data, BMD), (2) cryomicrotomy (used to determine soft tissue geometry and attachment points by sectioning a frozen specimen at approximately 750 to 1250 micron intervals in the sagittal plane), and (3) measuring the sub-failure material properties of the cervical column (C2-T1), motion segments (two vertebrae with the intervertebral disc), and failure characteristics of C6 and C7. Quasi-static and dynamic material properties are determined in the following load conditions: flexion, extension, lateral bending, axial rotation, axial tension, axial compression, load relaxation, and combined loading.

The QCT database[6] contains the first comprehensive set of geometric and BMD information ever collected of normal healthy males and females ranging from 18-40 years, with a minimum height of 5'0" (152.4 cm). Female volunteers range from 90 to 165 lb (40.8 to 74.8 kg) and males from 120 to 240 lb (54.4 to 108.9 kg). When completed, 80 male and 50 female datasets will be collected. 3.0-mm helical scans from the base of C1 through T1 were obtained and reconstructed at 1.5-mm intervals. For the lumbar spine, 10-mm sequence axial scans of the L2, L3 and L4 vertebra were obtained at mid-depth.

To determine soft tissue properties of cervical spinal ligaments and intervertebral discs, an Instron device was used for the former and a custom designed Impactor was developed for the latter. The Instron force test machine is for uniaxial tests in an orientation that is representative of physiological conditions. It is capable of a velocity of approximately 1.5 m/s and a maximum force of approximately 4000 N. An important design parameter when manufacturing the test fixture was to maintain a physiological environment, so the ligaments were mounted as they are *in vivo*. As such, the entire fixture was an enclosed environmental chamber, which was used to provide a controlled temperature of 37.2°C ± 0.6°C and a controlled humidity > 90%. The Impactor applies a local deformation with a hemispherical impactor to the disc. To control the impact, the fixture features an accelerometer, load cell, and X-Y positioning device. Eight anterior and four posterior sites were selected for testing around the annulus fibrosis on discs at the C2/C3, C4/C5, and C6/C7 levels. Ligament testing included the anterior longitudinal (ALL), posterior longitudinal (PLL), ligamentum flavum (LF), and supraspinous (SS) isolated from each cervical spine at C3-C4, C5-C6, and C7-T1. After preconditioning at 10% strain, each ligament was subjected to a 25% strain step, a 50% strain step, and a 50% strain oscillatory test. Failure loads were also determined.

A viscoelastic model is under development to characterize the force response of cervical spinal ligaments[12] and intervertebral discs. This is done by using the response of the lower step strain to predict the response of the oscillatory strain of varying frequencies and a step strain of a different magnitude. With this approach, it is possible to identify failure characteristics and develop injury risk functions.

MODELING:

The experimental data collected on the cervical spine structural and material properties is used by Southwest Research Institute to define required probability distributions. NESSUS and LS-DYNA computing tools are used to simulate uncertainty and variability including loads (*e.g.* impact acceleration during high speed ejection), material properties (*e.g.* vertebrae elasticity constant, Poisson's ratio), and geometries, and to compute the probability of exceeding certain injury tolerance levels. The analysis relates the spinal response probability distributions and the input probabilistic distributions. A parameterized approach allows for rapid reconfiguration of the model to account for differences in anthropometry and gender. As the model is developed, an integrated model verification / validation procedure is employed to test model predictions against both quasi-static and dynamic test results. This reduces the model development time by ensuring internal consistency and the validity of the mathematical processes and assumptions as the model expands.

A probabilistic parameterized finite element model of C1-C7 vertebral bodies, ligaments, and discs has been created using the QCT, cryomicrotomy, and materials properties data.[15] Figure 1 contains a finite element mesh model of the female cervical spine constructed using the averaged 106-120 lb. QCT data.

A mesh generation program has been developed that enables the vertebral bodies to be reconstructed automatically as new QCT vertebral body parameters are available. This allows the rapid generation of finite element models of individual subjects (e.g. small female vs. large females, etc.) to investigate individual cervical spine responses to specific inputs. Furthermore, geometric perturbations can be created to investigate the deterministic and probabilistic sensitivities of the geometry to injury prediction.

QUESTIONNAIRE:

An aircrew neck pain questionnaire has been developed for the US Navy based on a survey previously distributed by DRDC-Toronto and the US Army Aeromedical Research Laboratory (USAARL). This is being distributed by the US Naval Safety Center as part of their regular squadron inspections. To date, returns from F/A-18 pilots (49 male), EA6-B aircrew (43 male, 5 female), and helicopter aircrew (47 male, 2 female) from a variety of platforms have been received. Most of the respondents have flown with NVG. The results will be pooled as part of a TTCP HUM-TP7 collaboration.

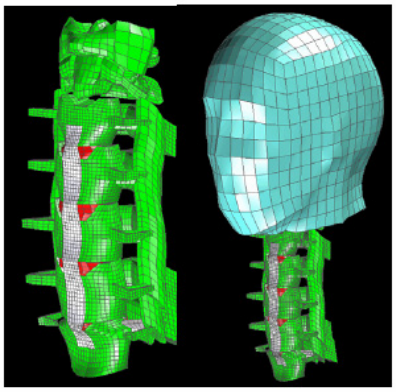

Figure 1. Female C0-C7 finite element mesh created using averaged QCT geometry parameters.

STRENGTH DATA:

To determine voluntary neck strength limits, a fixture has been developed to measure isometric and dynamic peak strength (MVC, maximal voluntary contraction) and endurance[22]. The fixture provides a means to standardize posture, enables repeatable measurements, and computer controlled feedback ensures that all volunteers received the same verbal encouragement and timing cues. In addition to strength measurements in flexion (forward and lateral), extension, and rotation, anthropometric, cervical range of motion, and electromyographic (EMG) data from the sternocleidomastoid, splenius capitis (SC), and trapezius muscles are also collected. Repeated measures are also performed to determine the effects of work/rest interval. These data are used to help set the lower boundary limits for non-injurious loading in the model.

PARACHUTE OPENING SHOCK EMULATOR:

Typically, programs rely heavily upon component and system level testing to identify and mitigate the performance and safety risks to the aviator during high-speed escape. However, parachute opening shock is the least controllable. Adding to the complexity is that matching initial test conditions will result in extremely different opening shock loads due to variations of propulsion performance, body motion, center of gravity variation, temperature effects, and other variable elements. A system capable of reproducing the parachute opening shock phase repeatedly, regardless of other conditions, would allow a parametric comparison of occupant sizes, advanced helmets, and other man-mounted equipment under identical conditions. Such a fixture was designed and fabricated to integrate with the NAVAIR Horizontal Accelerator facility.

The device consists of two main parts: 1) the seat structure is stationary and is used to control the initial position of the seat and manikin and 2) the net structure, which is accelerated down the track and serves to "haul" the manikin out of the seat simulating the parachute risers during the recovery phase of an ejection. The seat can be controlled in pitch only. Replicating the motion of a free seat in a yaw condition was deemed beyond the scope of this project. Tethers attached to the net structure, used to simulate the parachute risers, are connected to the manikin's torso harness. Due to the highly dynamic and chaotic nature of the event, extensive computer modeling was conducted using MADYMO to aid in designing and fabricating the test fixture. Some of the technical issues that were resolved using modeling include determining the required acceleration pulses, estimating the manikin velocity into the net and the transmitted loading into the structure, required length for the backup restraint, examining various designs for stopping the seat from rotating (resulted in complete redesign of seat structure), replicating realistic "free" seat motion using a pinned seat, and examining different material properties for the simulated parachute risers.

NECK INJURY MITIGATION

As an adjunct to the modeling program, an effort is underway to develop technologies that will mitigate the risk of neck injury during operational and emergency conditions. In order to be acceptable to the operational community, a practical solution to address these two threats must be incorporated into a single device. That concept must be integrated with existing survival vests, harnesses, helmets, and clothing. Finally, the device must not restrict cervical range of motion, interfere with cockpit controls, or add an unacceptable thermal burden to aircrews. To meet this challenge, a device modeled on the automotive racing industry Head And Neck Support (HANS®) that is reconfigured for the aerospace environment has been prototyped[16]. This device, called the AIR-HANS (Aircrew Integrated Restraint - HANS), has been integrated with the AIRSAVE and USN helicopter helmet (HGU-84/P) and the PCU-56/P parachute harness and tactical (HGU-68/P) helmet. Preliminary form-fit trials in an F/A-18E simulator to determine range of motion and reach have been conducted. Hubbard-Downing, the HANS® manufacturer, will fabricate the modified device and provide engineering support during dynamic validation tests to be conducted in FY06.

RESULTS

To date QCT data from 33 female and 53 male volunteers have been collected. Males and females demonstrate a decreasing trend in mean BMD from neck to low back (Figure 2). Lumbar spine BMD is significantly lower than cervical and T1. BMD among lumbar vertebrae are essentially the same, but there are significant differences between upper and lower neck vertebrae[24]. Preliminary results indicate a significant gender effect for BMD with mean female BMD greater than male. Mean female BMD were 265.9 ± 33.0, 206.3 ± 31.6, and 175.5 ± 21.3 mg/cc and mean male BMD were 255.5 ± 47.5, 190.3 ± 44.3, 170.9 ± 29.4 mg/cc for C2-C7, T1, and L2-L4 groups respectively.

Results from the studies to characterize the sub-failure and failure characteristics of male and female cervical ligaments were used to develop injury risk functions using a quasi-linear viscoelastic theory. Based on these studies, the peak forces corresponding to a 50% probability of injury to the PLL, ALL, and LF were 375 N, 275 N, and 195 N, respectively[13].

Preliminary results from the neck pain survey indicated that over 50% of respondents experienced pain related to flying: Pain during flight: TACAIR (39%), attack (44%), rotary (33%); Pain after flight: TACAIR (47%), attack (38%), rotary (35%). Pain was primarily described as mild to moderate with four reporting severe pain during and seven after flight. Incidences described as "worst" pain, typically last up to 24h post flight. Ten TACAIR pilots indicated that "worst" pain incidences lasted 1-4d post flight. Eight aircrew sought treatment for symptoms. Pain of four respondents resulted in grounding for less than a week.

Initial results of the isometric strength study indicate that (1) isometric extension is stronger than flexion; (2) during endurance trials, maximum extension and forward root-mean-square amplitude EMG values (normalized to the MVC) were often greater than 100% of the peak MVC values; and (3) isometric endurance time is lowest in forward flexion. There were differences in root mean square EMG magnitude and EMG median frequency (an indicator of fatigue) based on neck circumference. Typically, volunteers with the smallest neck circumference, measured at the base of the neck, demonstrated the shortest endurance time.

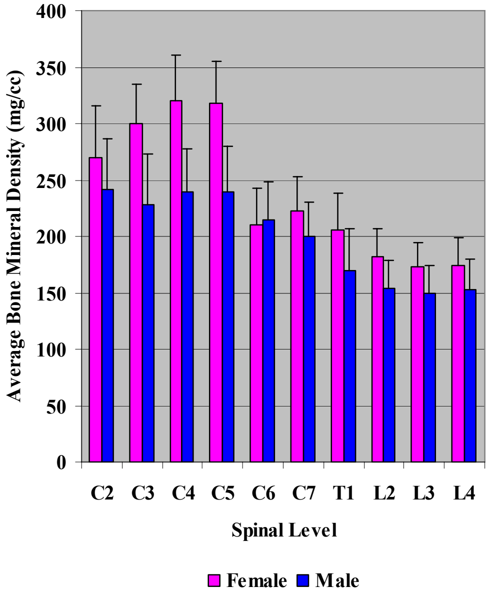

Figure 2. Averaged BMD determined from spiral QCT studies of healthy males and females.

FUTURE WORK

The program plan includes completing a high fidelity cervical model capable of AIS 3+ predictions by FY06 and AIS 1+ estimates by FY07. The high fidelity model of the lumbar spine will be complete by the end of FY07. A high fidelity representation of the neck musculature will be developed over the next two years. The effects of aging on the cervical ligaments will be determined and added to the model. To aid in the modeling of soft tissues, the effects of the added head weight on cervical soft tissues will be determined on volunteers using a standing MRI device with a custom fixture the represents a tactical ejection seat. Sub-injurious neck data from human volunteers studied at the former Naval Biodynamics Lab will be used to assist in the validation of the model predictions.

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BIOGRAPHY

Barry S. Shender, Ph.D. has worked for the NAVAIR Human Systems Department since 1987 at Warminster and Patuxent River. He currently holds the position of NAVAIR Human Systems Senior Scientist and is a NAVAIR Fellow. Dr. Shender is a Fellow of the Aerospace Medical Association (AsMA) and the Chair of AsMA Science and Technology Committee. He led the team that received the 2003 SAFE Association Award for Team Achievement for the Aircrew Integrated Life Support System program. His technical accomplishments have focused on life support in aviation systems, specifically in determining the relationship between physiologic and cognitive and motor responses to exposures to environmental stresses and the prevention of spinal injury during maneuvering flight, ejection and crash. He is the program manager of two ONR Future Naval Capabilities Warfighter Protection programs in the areas of Injury Prevention and Aircrew Integrated Life Support Systems. Both programs include joint service participation through Defense Technology Objectives and Joint Warfighter Capability Objectives. He has over 68 publications in the crew protection, physiology, and human performance.

Glenn Paskoff is a Biomechanics Engineer for the Naval Air Warfare Center, Aircraft Division, Patuxent River, MD. Mr. Paskoff received his B.S. in Mechanical Engineering from Penn State in 1991 and his M.S. in Biomedical Engineering from the University of Virginia in 1995. He received a Research Assistantship at the Automobile Safety Laboratory in Virginia where he gained extensive experience in injury analysis, subject preparation and testing protocols. Since beginning his career with the Navy, Mr. Paskoff has been involved in all aspects of escape systems research, development, design, testing, computer simulation, analysis and evaluation, management, and support related to the protection of aviators from injury resulting from high-speed ejection and crash.