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NORTH ATLANTIC TREATY ORGANIZATION

RESEARCH AND TECHNOLOGY ORGANIZATION
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RTO MEETING PROCEEDINGS 56

Soldier Mobility: Innovations in Load Carriage System Design and Evaluation

(la Mobilité du combattant : innovations dans la conception et l'évaluation des gilets d'intervention)

Papers presented at the RTO Human Factors and Medicine Panel (HFM) Specialists' Meeting held in Kingston, Canada, 27-29 June 2000.

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RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote cooperative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective coordination with other NATO bodies involved in R&T activities.

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• HFM	Human Factors and Medicine Panel
• IST	Information Systems Technology Panel
• NMSG	NATO Modelling and Simulation Group
• SAS	Studies, Analysis and Simulation Panel
• SCI	Systems Concepts and Integration Panel
• SET	Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

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Soldier Mobility: Innovations in Load Carriage System Design and Evaluation

(RTO MP-056 / HFM-043)

Executive Summary

Many NATO nations have soldier modernization programmes that aim to equip soldiers with fully-integrated state-of-the-art technologies that will enhance the five NATO soldier capability areas: lethality, protection, mobility, sustainability, and command and control. Military load carriage systems (LCS), which include clothing and personal equipment designed to carry the range of soldier loads, can have an impact on all of these capability areas. In particular, LCS are critical to soldier mobility and sustainability, and ultimately, to soldier performance and survival on the battlefield. In order to develop advanced integrated LCS that will actually enhance the performance, safety and comfort of the future fighting NATO soldier, it is necessary to further NATO's collective understanding of the factors affecting human LC capabilities, and the interactions between relevant components of the soldier system.

Scientists and equipment designers from NATO, PfP and non-NATO nationals from 10 nations met in Kingston, Canada on 27-29 June 2000 for a Specialists' Meeting sponsored by the Human Factors and Medicine Panel (HFM) of NATO's Research and Technology Organization. Participants examined the current state of knowledge in LC, exchanged findings from recent research and development efforts, explored what initiatives were needed to develop new concepts in design and evaluation, and identified opportunities for collaboration. Specific sessions were held on the physiology, biomechanics and performance measures of LC, approaches and tools for assessment, development and validation of objective tests and their use in design solutions, mathematical modeling, and the accuracy of pressure sensor measurement systems. There were two keynote addresses, 25 scientific research papers, four workshops and tours of research facilities at Queen's University during the Specialists' Meeting.

Soldiers must be able to carry heavy loads under a range of hostile environmental and operational conditions while maintaining peak performance for other demanding battlefield tasks. This poses a complex matrix of unique requirements for military LCS and demands a comprehensive understanding of the factors that contribute to human LC tolerance and ultimate soldier operational effectiveness. Physiological research has provided mathematical equations that will allow to evaluate the 'total time of marching' expectations for a specific mission. However, these estimates do not take into account any localized fatigue, discomfort, and/or injury. Soldiers experience up to two times the actual weight carried and specific body regions become fatigued before total body fatigue. Results obtained from instrumented backpacks (or biomechanical gait analysis) can be used to improve the design of personal LCS and to develop mathematical algorithms and improved models of LC to estimate the rest time needed to recover. Further research is recommended to develop predictive tools that may be used in future to maximize NATO soldier performance.

Innovative thoughts on energy transfer between the LCS and the person were presented and discussed. Once the mechanism for these energy transfers is understood, it should be possible to create a "smart" suspension system that will optimize load transfer and load control for the individual and the operational circumstances, and to design "tunable" LCS that give energy back to the soldier during the gait cycle. To accomplish this, further research is needed. A cross-comparison of objective measures and human trial findings should yield similar results for the same systems and generate design strategies needed to "lighten the load".

Because of the need to optimize LC for soldier mobility, sustainability, performance and survival, NATO countries should consider working together. Improved models, as well as more efficient and reliable, objective test methods and performance criteria are needed. The current STANAG for LC gives general design guidance only and does not help identify poor designs. As a result, many nations experience difficulties writing requirements or procurement specifications that will ensure the design or supply of improved LCS. The current STANAG should be improved by including efficient standardized testing and minimum objective performance specifications that are related to human tolerance and soldier acceptability. This would require that military scientists from interested NATO countries meet to develop a common research plan. The product of this collaborative effort would be standardization, interoperability and the enhancement of the mobility, sustainability and ultimate performance of NATO soldiers in future.

la Mobilité du combattant : innovations dans la conception et l'évaluation des gilets d'intervention

(RTO MP-056 / HFM-043)

Synthèse

De nombreux pays de l'OTAN ont mis en place des programmes de modernisation visant à doter le combattant de l'OTAN des dernières technologies intégrées afin d'apporter des améliorations aux cinq domaines opérationnels suivants : la létalité, la protection, la mobilité, la soutenabilité et le commandement et contrôle. Les gilets d'intervention militaires (LCS), qui comprennent l'habillement et l'équipement individuel destinés à recevoir l'ensemble des charges transportées par le soldat, peuvent avoir un impact sur chacun de ces domaines. En particulier, les LCS sont décisifs pour la mobilité et la soutenabilité du soldat, et en dernière analyse, pour les performances et la capacité de survie du soldat sur le champ de bataille. Afin de développer des systèmes LCS intégrés de pointe, susceptibles d'apporter de véritables améliorations des performances, de la sécurité et du confort du futur combattant de l'OTAN, il est nécessaire d'approfondir les connaissances des pays membres de l'Alliance concernant les facteurs ayant une influence sur les capacités humaines de transport de charges (LC), ainsi que les interactions entre les composants incontournables du fantassin.

Des scientifiques et des concepteurs d'équipements des pays de l'OTAN, des pays du PpP et de 10 autres pays se sont réunis à Kingston au Canada du 27 au 29 juin 2000 dans le cadre d'une réunion de spécialistes organisée par la commission sur les Facteurs Humains et la Médecine (HFM) de l'Organisation pour la Recherche et la Technologie de l'OTAN. Les participants ont examiné l'état actuel des connaissances en LC, ont échangé les résultats de différents projets récents de recherche et développement, ont réfléchi aux initiatives à prendre pour permettre le développement de nouveaux concepts de création et d'évaluation, et ont identifié des possibilités de coopération. Des sessions individuelles ont été organisées sur : la physiologie, la biomécanique et le calcul des performances en LC; les outils et les méthodes de développement, d'évaluation et de validation d'essais objectifs; la mise en oeuvre de tels outils et méthodes pour la conception, la modélisation mathématique et l'amélioration de la précision des capteurs de pression. Le programme de la réunion comportait 2 discours d'ouverture, 25 communications scientifiques, 4 ateliers et plusieurs visites des installations de l'Université du Queens.

Le combattant doit être capable de porter des charges importantes dans un large éventail de conditions opérationnelles et environnementales hostiles tout en maintenant ses performances au plus haut niveau pour faire face à d'autres tâches exigeantes de combat. Cela représente une combinaison complexe de besoins uniques en LCS militaires et nécessite une compréhension globale des facteurs qui contribuent à la tolérance humaine du LC et à l'efficacité optimale du combattant sur le champ de bataille. La recherche physiologique a fourni des équations mathématiques qui permettront d'évaluer le "temps global de marche" prévue pour une mission donnée. Cependant, ces estimations ne tiennent pas compte d'éventuels cas de fatigue, malaise et/ou blessure localisés. En règle générale, le soldat ressent jusqu'à deux fois la charge réellement portée et certaines parties de son corps fatiguent avant l'apparition d'une fatigue généralisée du corps. Des résultats obtenus à partir de sacs à dos instrumentés (ou de l'analyse biomécanique de la démarche) peuvent être utilisés pour améliorer la conception des LCS individuels et pour développer des algorithmes mathématiques et des modèles améliorés de matériel LC afin de pouvoir estimer le temps de récupération nécessaire. Il est recommandé de poursuivre les recherches dans ce domaine afin de développer des outils de prévision qui pourraient être mis en oeuvre à l'avenir pour améliorer les performances des soldats de l'OTAN.

Des idées novatrices sur les transferts d'énergie entre le LCS et le porteur ont été présentées et discutées. Une fois que les mécanismes permettant ces transferts d'énergie auront été compris, il

devrait être possible de créer un système de suspension “intelligent” qui optimisera le transfert et le contrôle des charges en fonction de l’individu et des circonstances opérationnelles, ainsi que des LCS “accordables” qui rediffuseront de l’énergie au soldat pendant le cycle de marche. Des travaux de recherche supplémentaires sont nécessaires pour y parvenir. Une comparaison contradictoire entre mesures réalistes et résultats d’essais sur l’homme devrait donner des résultats équivalents pour des systèmes similaires et permettre d’élaborer les stratégies de conception nécessaires pour “alléger le fardeau”.

Vu la nécessité d’optimiser le matériel LC du point de vue de la mobilité, la capacité de soutien, les performances et la survie des soldats de l’OTAN, les pays membres de l’Alliance devraient réfléchir aux possibilités de coopération dans ce domaine. Il y a lieu de prévoir des modèles améliorés, ainsi que des méthodes d’essais objectives et des critères de performances plus efficaces et fiables. L’actuel STANAG régissant le matériel LC ne fournit que des directives de la conception générales, et ne permet pas d’identifier les conceptions inadaptées. Par conséquent, bon nombre de pays membres ont de la difficulté à rédiger les spécifications de besoins ou d’approvisionnement susceptibles d’assurer la conception ou la fourniture de LCS améliorés. L’actuel STANAG devrait être amélioré en y ajoutant des procédures d’essais normalisées et des spécifications objectives de performances minimales en relation avec la tolérance humaine et l’acceptabilité par le combattant. Pour cela, il est important que les scientifiques militaires des pays de l’OTAN intéressés par ce sujet se rencontrent pour élaborer ensemble un plan commun de recherche. Cet effort de collaboration aurait pour résultat la normalisation, l’interopérabilité et l’amélioration de la mobilité, de la capacité de soutien et des performances ultimes des soldats de l’OTAN à l’avenir.

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Technical Evaluation Report

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INTRODUCTION

On 27-29 June 2000, NATO and Partners for Peace scientists, engineers and designers from military, academic and commercial organizations met in Kingston, Canada for a Specialist’s meeting organized by the Human Factors and Medicine Panel (HFM). The meeting on “Soldier Mobility: Innovations in Load Carriage System Design and Evaluation” was held at Fort Frontenac in Kingston, Canada with local sponsorship and management by the Canadian Defence and Civil Institute of Environmental Medicine (DCIEM) and Queen’s University. The purpose of the meeting was to bring together defence scientists, academic scientists, military load carriage procurement personnel and interested civilian pack manufacturers to examine the current state of knowledge in load carriage, exchange findings from recent research and development initiatives, explore what initiatives are needed to develop new concepts in design and evaluation, and identify opportunities for collaboration. There were two keynote addresses, twenty-seven scientific and technical papers, four workshops on future directions and tours of load carriage research facilities during the conference. There were 67 registrants from 10 countries with papers given by scientists from France, Germany, Netherlands, United Kingdom, United States and Canada.

THEME / OVERVIEW

Load carriage systems (LCS) are critical to soldier mobility, survival, sustainability and soldiers’ ultimate performance on the battlefield. These include clothing and personal equipment designed to carry the soldier’s fighting, battle and sustainment loads, and must allow the soldier to complete all missions and tasks in all military environments and scenarios with minimum degradation in performance. An improved understanding of the factors affecting human load carriage capabilities, and the interactions between relevant components of the soldier system, is required in the development of advanced integrated load carriage systems that will enhance the performance, safety and comfort of the future fighting NATO soldier. Improved biomechanical and physical models, as well as more efficient and reliable objective test methods are needed to facilitate rapid iterative development and evaluation of soldier load carriage systems for the future. The purpose of this specialist’s meeting was to bring together experts in military load carriage system analysis, design and evaluation (from the domains of Human Factors, Biomechanics, Medicine, and Industrial Engineering) to share latest developments in design technologies and approaches, evaluation methods and equipment, and load carriage system design and integration.

SYMPOSIUM PROGRAM

The overall symposium was chaired by Major Linda Bossi, DCIEM Canada with invited chairs for each of the seven sessions. The Program Review Committee was chaired by Major Bossi with members being Dr. Paul Gorzerino (FR), Dr. John Obusek (USA), Dr. Reg Withey (UK), Dr. Tom McLellan, (CAN) and Dr. Joan Stevenson (CAN). In a typical Kingston welcome, dignitaries were ushered in by a bagpiper and delegates were welcomed by the city of Kingston Mayor G. Bennett, Commander of the Land Force Doctrine and Training System (LFDTS), Major-General J. Arp, CD, and Principal of the Royal Military College, Dr. J. Cowan, with some opening remarks about the historic importance of Kingston provided by Scientific Advisor to LFDTS, Dr. K. Ackles.

The two keynote speakers were strategically positioned at the start of the first two days of the conference with Dr. J. Knapik (USA) providing an update on physiological, biomechanical and medical aspects of load carriage and Dr. R. Kram (USA) challenging current perceptions of load carriage by presenting examples of novel load carriage concepts from the animal kingdom.

Dr. Cornelius Wientjes of the RTA/HFM Panel Executive in Paris, France provided an overview of RTO's mandate in NATO and described their funded activities. There are numerous military panels of NATO and this Specialist Meeting was run under the auspices of the Human Factors and Medicine (HFM) Panel.

Sessions I and II, entitled *"Physiology and Biomechanics of Load Carriage"* were chaired by Col. Paul Gorzerino MD from France and Dr Ira Jacobs from Canada, respectively, and seven papers were presented. Session III, chaired by Dr. J. Stevenson of Canada, examined *"Load Carriage by Women"*. These papers focused primarily on physiological and biomechanical responses to load carriage under different conditions.

Sessions IV and V focused on *"Load Carriage Biomechanical Assessment Tools"* and *"Development of New Load Carriage Systems"* and were chaired by Dr. Robin Hooper of the United Kingdom and Dr. Tim Bryant of Canada, respectively. The five papers in these sessions were devoted to an examination of the strategies used for the assessment of load carriage systems through objective, subjective and computer-aided testing and examples were given of iterative development of new systems.

Session VI was chaired by Dr. Reg Withey of the United Kingdom and highlighted the use of *"Biomechanics Tools in Design"* where specific design features and whole systems were discussed. Session VII focused on *"Skin Pressure Measurement"*, an important assessment tool for load carriage system design. This session was chaired by Dr. Carolyn Bensel of the United States. Session VIII *"Load Carriage Modelling"*, chaired by Dr. Evelyn Morin of Canada, highlighted the potential for computer based models to assist with the design process.

The Specialists' Meeting concluded with four workshops of interest to the future development of the research on load carriage. These workshops were *"Innovative Designs in Load Carriage"* chaired by Dr. J Stevenson (CAN), *"Portable Field Measurement Systems"* chaired by Dr. E. Morin (CAN), *"Standardization of Load Carriage System Testing"* chaired by Major Linda Bossi (CAN), and *"System Design and Fabrication Issues"* chaired by Dr. T. Bryant (CAN). Summaries of the workshop discussions are included as Appendices to this Technical Evaluation Report.

TECHNICAL EVALUATION

Key Note Addresses

The first keynote address by Dr. Joeseph Knapik provided a framework for understanding the important components of personal load carriage from a historical, physiological, biomechanical and medical perspective. It was interesting to note that soldiers now carry three times the load mass carried by ancient Greeks and Romans. Although this increase is due, in part, to increased body size, strength and perhaps training, it is also due to improved understanding of the effects of center of mass location and load distribution as well as improvements to the pack frame and varying the methods of load carriage. One measure of effectiveness when carrying loads is the metabolic energy cost (in watts) where the factors affecting performance are: subject's mass, load mass, velocity of marching as well as the slope and conditions of the terrain. Dr. Knapik presented models that used these variables to predict potential load carriage performance.

Injuries sustained during load carriage, although usually not debilitating, do affect individual mobility and hence the effectiveness of the entire unit. Most of the injuries result from inappropriate load mass, marching conditions or distances, clothing, personal attributes or environmental conditions. Foot blisters are the most common problem followed by other lower limb problems and back sprains. The incidence of foot blisters is thought to result from factors such as poor footwear, heavy loads, lack of training, added frictional forces due to sweating and inappropriate foot care. Metatarsalgia, stress fractures and knee problems are related primarily to load mass and duration of marching. Back problems appear to be related to exaggerated body lean angles with heavy loads that can affect disc compression and spinal muscular fatigue. The most common disabling injury that is related to design of load carriage systems is rucksack palsy, which results from entrapment of the brachial plexus by the lower shoulder strap in the armpit.

To maximize soldier performance and minimize injury, the first keynote speaker advocated reduction and redistribution of load mass, equipment modifications, and physical training programs. In addition, soldiers must have the knowledge and means to keep their feet dry to prevent foot blisters and the load carriage system must incorporate design strategies (i.e., waist belt, frame or sternum strap) to reduce the incidence of rucksack palsy.

The second keynote speaker, Dr. Rodger Kram, focused on developing a better understanding of the fundamental mechanisms underlying walking and running by examining gait through the laws of physics. He also challenged the registrants to examine the breadth of strategies that humans and animals use to carry loads, and by doing so, to query how these strategies could be applied to personal load carriage systems. The metabolic energy cost of load carriage depends upon the cost of performing external work, cost of generating muscular force to support the body weight and cost of swinging the limbs. Interestingly, metabolic energy costs do not parallel mechanical energy costs. For example, African women can carry loads on their heads with no increase in energy cost for loads up to 20% of body weight. However, this is not the situation for load carriage on the back or on the waist. This is also true for the rhinoceros beetle that can carry 30 times its body weight with only a four times increase in metabolic cost. By some mechanism, the mechanical energy is being recovered.

One explanation is that the energy is stored, transferred and returned to the system. For example, during human gait 93% of the energy stored within tendons and passive elements can be returned. It is thought that tendons act like springs and return energy, thus requiring less metabolic energy. This concept has been shown in kangaroo hopping at different speeds and load carrying where energy costs did not rise with increased demands. Transferring this example to human load carriage, people in Asia use springy bamboo poles that are very compliant with a low natural frequency of about 1/3 of step frequency. Mechanically, the poles reduced and smoothed out the force fluctuations but did not appear to lighten the load. Further work is needed to see if load carriage systems can be tuned to provide energy transfer, and continued research with animals and indigenous people will help in understanding the relationships between physiological and biomechanical energy costs.

Physiology of Load Carriage

Soldiers are often expected to carry heavy loads over long distances and rough terrain so much of the earlier research was focused on the physiological demands of load carriage in the 1970's and 1980's. With these studies, it was realized that as the payload increases, so do the physiological demands. It was also realized that as the speed of marching increased the metabolic costs also rose. The other modulating variables were terrain factors, environmental factors, and conditions of the load. These earlier studies led the way to a mathematical prediction equation that allowed military commanders to judge how much load soldiers could be expected to carry on certain missions. Although the approach was successful for this purpose, it was not designed to identify problems related to local fatigue, discomfort due to pack design or the biomechanical changes in internal work performed by the body.

Bigard (Paper #3) was intrigued with the unequal relationship between mechanical work performed and the metabolic energy expended which he defined as efficiency of load carriage. He defined total mechanical work as the internal kinetic motion (both translational and rotational) of body segments, the potential energy of segment motions and the unmeasured elastic energy within muscle tendons and other connective tissues. External work was defined in relation to position and speed changes of the center of mass with respect to the environment. The literature has shown that mechanical work does not increase as quickly as metabolic work with increasing loads, perhaps because the amount of total mechanical work cannot be validated. In addition, he believes that most studies are not long enough in duration to allow systemic metabolic measures to be evident over local fatigue measures. He encouraged scientists to integrate the physiological findings with the biomechanical and psycho-physical data to develop a better understanding of interacting variables and to improve assessment strategies.

This challenge was taken seriously by a series of four papers that tried to unravel the mystery of increasing load mass or increasing speed of gait from a physiological and biomechanical perspective. Using physiological measures, Polcyn et al. (Paper # 7), who varied load mass, found that for every 1 N increase in load carried, there was a 3% increase in time to complete a circuit and 2 % increase in metabolic cost. The payload carried could explain 40% of the variance in metabolic cost. Past researchers have assumed that the metabolic cost per kg load is independent of the total load mass carried centrally by the body. Holewijn and Meeuwsen (Paper #1) showed that he could explain oxygen uptake for different loads with different variables than Pandolf's earlier model. Holewijn and Meeuwsen found a non-linear response with increased loads using an equation that separated out the basic standing metabolic requirements, the metabolic costs due to body mass and pack motion (based on walking velocity) and the cost of the shoe mass (incorporating walking velocity). Holewijn and Meeuwsen also reported an interesting observation whereby heart rate values do not follow a constant relationship to oxygen consumption. The reason given for this fact was that load carriage involves a substantial static holding component that accentuates heart rate, creating a shift to higher values with increased load. Combining age and sex data on maximal aerobic consumption, Holewijn and Meeuwsen recommended a load limit value based on metabolic tolerance by sex and age to load carriage at 1.33 m/s. For example, for young soldiers, the recommended load limit would be 32 kg for men and 19 kg for women. These load limits dropped off with increasing age.

Biomechanics of Load Carriage

From a biomechanical perspective, moments and force variables from a link-segment model approach were related to load carried and gait speed. Harman et al. (Paper #5) and Polcyn et al. (Paper #7) found the expected increased ground reaction force, joint moments and bone on bone forces with increasing load. But the kinematics of gait changed substantively. When speed was increased, soldiers increased both their stride length and stride frequency, which resulted in greater ankle and hip range of motions. This resulted in an increased double support phase. The need for increased speed meant that the trunk was positioned with a greater forward lean angle. LaFiandra et al. (Paper # 6) examined the angular momentum changes occurring between the upper and lower body segments with increasing walking speeds and found that there was a reduction in angular momentum in both segments but a greater proportionate reduction in the upper body's angular momentum. This was thought to result from a reduced arm swing and momentum transfer from the lower body's angular momentum that may also conserve metabolic cost.

When load was increased, stride frequency increased but stride length decreased thus allowing more time in the double support phase. Ankle angles increased (more extension), but there was greater flexion of knees and hips with increased weight and an increased trunk lean angle. As a result of these different methods of accommodation to increased demands on the body, Harman et al. (Paper #5) did not find many interactions between main effect changes in load and gait speed. They concluded that the effects of load and speed increases were additive in that an increase in speed had the same directional effects regardless of load mass, and increased load effects were the same regardless of walking speed. Because of substantial gait changes that occurred between speeds of 1.3 m/s and 1.5 m/s and loads from 33kg to 47kg, they recommended that, when carrying heavy loads around 45 kg, walking speeds should be reduced to under 1.3 m/s (4.8 km/hr).

Holewijn and Meeuwsen (Paper # 1) and Harman et al. (Paper # 5) examined the increase in muscular requirements with increased loads using electromyography (EMG). Although the EMG amplitudes increased during increased loads, Holweijn, who calibrated them against maximal voluntary contractions (MVC), felt that they were not the limiting factor as the EMG amplitude increased by only 1.9% in 5.4 kg and 2.9% in 10.4 kg, below the recommended limit of 5% MVC to avoid muscular fatigue. Holewijn and Meeuwsen (Paper #1) also examined the point contact pressures under the shoulder straps for a shoulder-based pack and a customized pack that distributed the loads on the waist and shoulders. When a person was standing, the maximum pressures were 20 kPa (150mmHg) for 5.4 kg and 27 kPa for 10.4 kg loads over the top of the acromion. This point pressure increased to 35 kPa and 50 kPa for the shoulder-based pack at 5.4 kg and 10.4 kg respectively and 20 kPa and 23 kPa for customized pack at at 5.4 kg and 10.4 kg respectively. Based on literature, the blood supply to muscles is occluded at 10-14 kPa although Bossi et al. (Paper # 14) and Bryant et al. (Paper #15) were recommending 20 kPa tolerance limit based on soldiers' reported discomfort when wearing a backpack. Hip pressures were reported to be less problematic as this area is reported to be able to tolerate three times more contract pressure than the shoulders.

Johnson et al. (Paper #4) and Ling et al. (Paper # 10) studied the influence of load location on biomechanical and physiological measures. Johnson et al. placed a 36 kg load on men in high, medium, and low pack locations and balanced on the front and back of the body. Ling et al. place a 10 kg load on women in a shoulder-based backpack, around the waist, and diagonally across one shoulder. Results were similar to previous studies that reported balanced loads or loads around the waist as having less impact on gait parameters. The biggest concerns for these strategies are heat dissipation and overuse injuries from the lower limb and back.

Performance Measures during Load Carriage

One concern has been the performance of women in heavy load carriage situations where they are expected to perform equally to men based on common task criteria. Unfortunately most women, on average, have smaller anthropometric dimensions with less muscle mass and a smaller aerobic capacity, resulting in a greater physiological demand for a given load. Hence, finding strategies that allow women to succeed yet not risk operational effectiveness are important. Pandorf et al. (Paper #2) and Frykman et al. (Paper # 9) studied performance based on time and time on task during an army obstacle course. A number of measures representing anthropometry, aerobic capacity and muscular endurance as well as the U.S. Army Physical Fitness Test (APFT) were used to assess performance on the circuit while carrying 12kg, 27kg, and 41 kg loads. Circuit time was best predicted by aerobic capacity measures and muscular endurance measures, with body size also being important. Although prediction of performance is not possible with the APFT, the variables studied could be used as a first level screening if the selection criteria is set sufficiently low (i.e., one standard deviation below the mean) to guarantee that women who could perform the job are not falsely excluded.

Approaches and Tools for Assessment of Load Carriage Systems

A proper design process starts with knowing the operational requirements of the personal load carriage system for soldiers. This is not a simple exercise as there are many needs and complexities dictated by the mission and environmental requirements. Nonetheless, a written statement of requirements is necessary to sift through the quantity of items needed to define the essential requirements and features of a load carriage system. Although this phase can be conducted by operations leadership, it is the ordinary foot soldier who knows the aggravations felt with the current system and who will bear the consequences of design decisions in future systems. To integrate the user throughout the design process is the essence of an ergonomic approach to design.

An ergonomic approach was used by both the American and Canadian militaries in their most recent initiatives to develop new load carriage systems. In both cases, the scientists used soldiers' satisfaction with the current system as a benchmark for future changes. For the American Army, their benchmark was the ALICE system that was developed in 1990 (Sampson paper # 17) and for the Canadian Forces, their benchmark was the Canadian 1982 Pattern system (Bossi Paper # 18A). The ALICE pack was an internal framed system with webbing and the '82 Pattern was an external framed rucksack with webbing. Soldiers from both countries were dissatisfied with their system for different reasons. The American soldiers complained about durability, and the effectiveness of shoulder and waist belt straps. The Canadian soldiers complained about poor fit, load distribution and incompatibility with the webbing. These concerns and other such data served as the starting point for the iterative design process.

In the development of the two load carriage systems, slightly different user-centered approaches were developed. The American approach involved a central design team but different user groups to answer specific design questions or evaluate different iterations. The Canadian approach also had a central multidisciplinary design team, but tried to return to the same group of representative soldiers for feedback on any given design/feature iteration throughout their iterative process. In addition, the Canadian design team had access to the biomechanical evaluation and standardized assessment equipment funded by the Canadian Defence and Civil Institute for Environmental Medicine and stationed at Queen's University. At the time of this conference, both load carriage systems have gone through the majority of the iterative testing process and will soon be in production.

The MOLLE system, described by Sampson et al. (Paper #17) and Kirk, stands for MOdular Lightweight Load carrying Equipment and was initially expected to serve as a platform for basic soldier fighting and sustainment loads and electronics. The final definition of the MOLLE was based on having a sound load carriage system that could carry the necessary electronics. Although the goal was to design with load stability, load distribution, mission effectiveness, electronics and for airborne tasks, soldiers pressed the designers for more capacity and greater adjustability. Both were satisfied over the course of at least seven human field trials using questionnaires and focus groups involving more than 2000 soldiers. Soldiers especially liked the daisy-chain connectors that created pack adaptability. However, they did not like the inventive quick release mechanism and eventually convinced the design team to abandon this idea in favour of a more conventional waist belt and doffing system.

The Human Factors side of the Canadian load carriage system was described by Bossi and Tack (Paper #18A) in terms of the goals for the system and the process undertaken to reach these goals. User Panels were developed to validate requirements, assess the range of potential features and the various design iterations. Design began from the inside out starting with the load carriage vest, then the integrated patrol pack and rucksack. For each item, opposing designs and features were developed and evaluated with and by users to ensure as many design options as possible were considered. In the end, the Canadian system comprised a Tactical Vest, small pack and an internal framed large rucksack, each incorporating a series of daisy chains so that a range of accessory pouches and bags can be attached to achieve modularity and mission configurability. Sizing trials were conducted to make decisions about the fit envelope and size tarriffing of the variable-sized system. Implementation plans will focus on adequate soldier training with the new system, to ensure that soldiers will reap full advantage of system modularity and adjustability.

Use of Objective Tests

The Canadian approach involved a two-pronged approach: field trials and standardized objective testing. To assist with design and development of minimum performance criteria, Queen's University Ergonomics Research Laboratory was engaged to construct and validate a series of physical tests. Bossi et al. (Paper # 14) described the suite of biomechanical assessment tools and how they fit into the design process. The dynamic load carriage simulator is mounted with mannequins to represent the 95th and 50th percentile male and 50th and 5th percentile female for weight, height and critical girth and breadth measures. The mannequins are covered with a skin analog, Bocklite™, which was chosen because its response characteristics are very reproducible.

The simulator can be programmed to walk, jog or run in a consistent manner between trials. Using a set payload and standardized strap force settings with a lean angle to balance the moments of the pack-person system, the computer-controlled mannequin is programmed to walk or jog, based on whether marching or fighting orders conditions are being investigated. The outputs to measure the pack-person interactions are: average and peak pressures on the shoulders, back and waist, hip reaction forces and moments, pack-person motions and changes in the strap force tensions.

A second measurement tool is the load carriage compliance tester that is used to examine the stiffness of the suspension system of a pack. The computer-controlled device registers the angular position in degrees and the resistance to this motion in Newtons for a 50th percentile male mannequin during flexion, lateral bending and torsion. The third measurement tool is a static load distribution mannequin that is used for biomechanical modeling and examination of the impact of specific pack features such as, shoulder strap attachment points or effect of lateral stiffness rods.

Bryant et al. (Paper # 15) reported on the validation of these devices using a standardized testing circuit whereby soldiers were asked to march 6 km interspersed with specific tasks that required balance, agility and mobility in different conditions. Correlations were made between the standardized testing conditions and soldier reports to determine the variables best suited to set minimal acceptable performance standards. Based on discomfort scores by soldiers, the suggested performance criteria for superior packs were under: 14 mm of pack-person motion, 20 kPa of average pressure and 45 kPa of continuous peak pressure and, based on biomechanical modeling, less than 290 N of shoulder reaction forces and 135 N of lumbar reaction force.

Design Solutions to Specific Problems

In any design problem, specific decisions must be made about the pack materials to be used, the type of suspension system and how the system is designed and constructed. Davies (Paper # 18B) provided an excellent review of the types of fabrics, foams and fittings used in load carriage systems. The most important feature of pack fabrics, aside from their safety characteristics such as waterproofing, and chemical protection, is the durability of the materials. Davies offered advice about material deniers, sewing versus welding fabrics, buckles, fittings, webbings and tapes and the types of foams available for the interface.

A strategy for designing load carriage systems is the use of standardized assessment tools as demonstrated by members of the Queen's University Ergonomics Research Group. Using the Load Distribution mannequin, Reid and Whiteside (Paper #19) demonstrated the effectiveness of placing lateral rods in the suspension system of the pack. By separating the forces placed on the shoulders and waist belt, it was possible to determine that rods in the suspension system could shift as much as 10% of the force from the shoulders to the waist belt and provide an extensor moment to help the erector spinae with load carriage tasks. Reid et al. (Paper #20) studied the optimum location for the lower shoulder strap attachment point. An empirical study assessing different attachment point locations resulted in a determination that an angle from 24º to 30º with respect the vertical axes was best to minimize shoulder pressures. The standardized approach can answer specific design-based questions more quickly and cost-effectively than organizing human trials.

Stevenson et al. (Paper # 21) presented a series of studies to show how the assessment tools were used for the development of the new Canadian Clothe the Soldier (CTS) load carriage system. Here, the various iterations of the tactical vest, patrol pack and rucksack for the CTS system were tested on the simulators and compared to a database of previously tested packs. The CTS system was among the top 10% of packs in the database on one third of the variables tested and above average on the remaining variables. The standardized approach can help the design process as it can be done more quickly and more cheaply than human trials, permitting more design iterations. The approach augments but cannot replace human trials for input on functionality, features, adaptability and acceptability by soldiers.

Accuracy and Sensitivity of Pressure Measurement Systems

The types of measurements needed for load carriage include the ability to measure force, motion and skin contact pressure. Since discomfort appears to be related to high contact pressures, the ‘state of the art’ in skin contact pressure technology was reviewed. Three research groups have been working with the Tekscan™ technology, primarily because it has thin and less expensive sensors than most other technologies. Wilson et al. (Paper #23) calibrated the I-Scan system and found that it was accurate within 3% using a flat calibrator system. Morin et al. (Paper # 24) used the F-Scan unit and calibrated it on a flat surface and, with a hand-held calibrator, on a flat surface, on the mannequin and on a human. They found that as the surface compliance increased, so did the variability in the recordings. Martin and Hooper (Paper # 22) conducted a test-retest using the F-Scan pressure sensors on the human body with 92% of sensels giving the same reading and no errors greater than a 10% difference. They found the F-Scan system valuable for investigating different types of shoulder padding (i.e., foam or air mesh) and a number of different strap widths, mesh conditions and waist belt designs. Despite difficulties in verifying the absolute measures for pressure, they found consistency of measurement on a person and agreement with rater discomfort scores. They believed that for comparative purposes, this pressure measurement system has potential to assist with design improvements.

In summary, an accurate measurement of skin contact pressure is required for valuable feedback of soldier discomfort. Using current technology in comparative methods of analyzing pack characteristics appears to be effective; however, confidence in the absolute accuracy of the pressure results remains illusive. Whether improved technology or improved calibration is the answer, the establishment of absolute pressure values as performance criteria for pack designs must be guarded by at least a 10% to 20% error band. For comparative studies, error bands in the range of 10% may be appropriate. However, the measurement system is valuable for locating peak pressure points.

Mathematical Modeling of Systems

Mathematical modeling allows the designer, researcher or military customer to see the potential effect of a particular load carriage design or payload before developing a new design. However, the accuracy of the inputs is critical to developing a successful model. Pelot et al. (Paper # 25) reported on a second generation static model developed with the aide of the Load Distribution mannequin. This model had shoulder straps and a waist belt with the shoulder straps modeled as a pulley system and the waist belt modeled as two semi-circular cones and an angled back and flat waist joining them. This model was within 10% accuracy of predicted output values. Pelot et al. used this model to demonstrate some of the design-based questions that can be answered with a modeling approach.

Two dynamic modeling approaches are underway. Gretton and Howard (Paper #27) are working toward the potential of a dynamic model. They have put energy into building an appropriate test mannequin so that they can collect dynamic data required to identify mathematical pack suspension models. The test-rig can generate a quasi-sinusoidal motion using a hydraulic ram, and a triaxial accelerometer can gather the pack’s motion. Dr. Playter of Boston Dynamics gave an excellent presentation of a human soldier simulation whereby human motion and pack response characteristics were input into the computer and the resultant motions shown. This computer model has excellent graphics but its accuracy for the expected responses of soldier's actions is dependant upon developing accurate human motion profiles for tasks and accurate inertial properties for the pack.

Undoubtedly, biomechanical modeling can be an asset to future understanding of pack-based forces for design, tissue tolerance limits and predicting motion responses under certain movement conditions. However, modeling the pack-person system is not a simple task because of the redundancy in the system, difficulty in measuring forces and the compliance of the pack. Nonetheless, working toward a better understanding of the manner in which a pack works will allow researchers and designers to develop new concepts in design.

WORKSHOPS

The conference concluded with four workshops that built upon the scientific presentations and interactions of researchers. In the *Innovative Designs Workshop*, participants focused on the key factors of energy cost, payload weight, modularity comfort and training. For each possible strategy of load carriage (head, shoulders, trunk and waist), the participants discussed the design principles for that strategy. In conclusion, it was felt that a design break-though was still possible in load carriage. In the *Standardization of Load Carriage Testing* workshop, researchers struggled with the factors of what to measure and how to measure it. If a NATO group wished to develop a STANAG, then determining the essential items upon which to establish standards is an important issue. It is also essential that these standards be validated by soldiers' responses under testing conditions and implemented in such a way that more than one country can conduct the tests. The initial work by Queen's could be used as a starting point for a STANAG. The *Portable Field Measurement System* discussion centered around appropriate measures to take, given the enormity of the potential to measure biological signals. It was felt that such a device should be modular, lightweight, durable and relatively low cost. Issues of data storage, demarcation of data sets and strategy of analysis are critical decisions that need to be made during the development process. In the workshop on *System Design and Fabrication,* participants identified key technical issues that require further clarification or standardization. Commercial backpacks offer features that many military packs lack, such as additional fit adjustment and load control features and ability to adjust loads during use. There is recognition of the unique requirements of military users that need to be taken into account when these design features are included – for example, the importance of access to critical mission equipment (e.g., magazines, protective respirators). Participants highlighted the importance of soldier-user involvement throughout the development process and the criticality of educating designers, equipment issuers and users in order to achieve design and implementation success.

SUMMARY

Many NATO nations have soldier modernization programmes that aim to equip soldiers with fully-integrated advanced state-of-the-art technologies to enhance the five NATO soldier capability areas: lethality, protection, mobility, sustainment and command and control. Military load carriage systems can have an impact on all of these capability areas, especially those of mobility and sustainment. The research in load carriage falls into the two main areas of basic and applied research. The basic research deals mainly with humans' biomechanical, physiological or subjective responses under different load carrying conditions, simulations of human responses using physical and mathematical models (such as simulators) and the use of various measurement technologies to capture these responses. The applied research delves into human and simulator testing for specific design-based problems (e.g., types of shoulder straps or waist belts) and development of new load carriage systems. Together, these papers provide an up-to-date comprehensive body of knowledge about load carriage. The challenge remains to understand the biomechanical aspects of load carriage as well as we understand the physiological aspects and then to use this information not only to develop new and innovative load carriage systems but also to develop minimum performance criteria based on tissue tolerance data for load carriage. To accomplish this task, the NATO and PfP countries will need to continue to work together on this problem.

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ATTACHMENTS

Appendix 1	Summary of Innovative Designs Workshop – facilitated by Dr. Joan Stevenson
Appendix 2	Summary of Standardization of Load Carriage Testing Workshop – facilitated by Major Linda Bossi
Appendix 3	Summary of Portable Field Measurement System Workshop – facilitated by Dr. Evelyn Morin
Appendix 4	Summary of Workshop on System Design and Fabrication - facilitiated by Dr. Tim Bryant

Workshop Session: Innovative Designs for Load Carriage

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Workshop Objective

The workshop focused on innovative design for load carriage and had approximately 16 participants from a variety of NATO countries. The workshop was highly interactive with a mixed audience of designers, researchers and operations personnel. The goal of the workshop was to identify principles that could be followed in new designs and give practical examples of specific design concepts or features that might meet these principles.

Concerns with Current Designs

The specific design concerns were identified that affect implementation of load carriage design. Although more items could be added to the list, only the following points were discussed: conserving energy cost, examining the payload requirements, the importance of modularity, maximizing soldier comfort, training soldiers and changing military attitudes about load carriage.

Energy Cost

The energy cost of human load carriage is one of the most important factors to control. Metabolic energy demands can be reduced by having the center of gravity of the load as close as possible to the body. Both slim packs, that keep the weight close to the body, and packs with the center of mass higher and close to the shoulder blades are current strategies used to accomplish this principle. In a review article by Knapik et al. (1996), they reported on the physiological energy costs of level walking, various walking speeds, types of terrain, and climatic conditions. Some researchers have developed regression equations to predict energy costs of military performance and thus predict how long it will take troops to arrive at various sites (Epstein et al., 1987). A number of studies have investigated different methods of carrying to reduce the metabolic energy costs and discomfort in carrying loads. Although demands can be reduced by the pack arrangement, by far the least energy demands occur when the weight is evenly distributed to the front and back of the body (Kinoshita, 1985; Knapik et al., 1997). This strategy has the effect of bringing the force of the load directly through the spinal column and eliminating moments of force. Unfortunately, interference with human movements, mission demands and cooling the body minimized this approach to personal load carriage in military environments.

Weight of Payload

Without fail the largest component of energy demands rests with the payload weight itself. There seem to be two operational truths within load carriage; namely, that if the load is within human capacity, soldiers will carry more weight; and larger soldiers tend to carry more than smaller soldiers, despite military doctrine that states each individual must carry the same weight and their own items. Platoons tend to work in teams and make adjustments within the team based on the ability of the soldiers. In other words, despite the fact that everyone must carry their own kit, they do switch heavy weapons and ammunitions from one person to another.

Modularity

Another design principle that is important to military requirements and soldier preferences is improved modularity. For example, if a unit is going on a two week expedition, different kit would be required than during a two day or two hour operation. The ability to attach different items such as ladders, ammunition or weapons would be helpful. However, it is not only necessary to design modularity into personal load carriage systems, but also necessary to change the attitudes of senior military officers and soldiers in this regard. Soldiers can only take advantage of the modularity afforded by new system designs if there is less concern from military leadership about uniformity of appearance (although it is recognized that certain items such as auto-injectors (chemical agent treatment) must be stored by all users in the same location for safety). The difficulty is also creating modularity without losing structural strength and performance of the system.

Soldier Comfort

One of the biggest problems with backpacks is the trade-off between simplicity and flexibility of the system to be configured optimally for each person. Comfort is related to load location, load mass, as well as the strain placed on specific body parts such as the shoulders or lumbar area. In these regions, muscles are forced to work without a blood flow because of the occlusion that occurs in these regions due to the pack load. In addition, factors such as peak pressure points or chaffing also lead to discomfort among soldiers (Knapik et al., 1996). Currently, users are provided with the ability to adjust the load carriage system from shoulders to the hips and vice versa in order to gain some relief to these areas. Even subtle movements can provide temporary relief. Current packs have added features such as sternum straps, load lifter straps and hip stabilizer straps to help alleviate pressure points and muscular fatigue. But soldiers must be given instructions about their purpose and strategies in proper adjustments.

Training

Another aspect of more advanced load carriage systems is that soldiers would require more training to fit and adjust the system. It is also important that methods of adjustment be self evident through the design, otherwise adjustments might not be used. One only needs to examine human behaviour with ergonomically –designed office chairs where users either don’t adjust them properly in the first place or fail to keep re-adjusting and changing over the course of a day. An ergonomically–designed load carriage system, with the same ability for adjustments, would be wasted for comfort and fit if the soldiers did not use these adjustments. As with newer designs in office chairs, it may be necessary to have an automatically adjusting system, thus assisting the soldier without expecting him or her to initiate changes.

Principles of Superior Design

The three main principles of good design are function, fit and features. But these principles must be matched to the human’s form where the spinal column, shoulder girdle and pelvic girdle serve the function of support for the body’s weight and use of the upper and lower limbs.

To maximize the use of these anatomical structures and minimize the demands on the musculoskeletal system, the forces should act directly downward through the spinal column, thus creating a primarily compressive force, and there should be no external pack moment, thus minimizing the muscular forces needed to counterbalance the load. Strategies that accomplish these criteria are: head carrying, shoulder carrying, trunk carrying, or waist carrying. Although these design concepts may not appear attainable at this time, the workshop members discussed them without restraint of feasibility or practicality.

Head carrying. Head carrying is used in many countries to carry large, awkward and heavy items. This approach is not acceptable in a military situation. However, one head-carrying feature, first used by fur-trading voyageurs then by backpackers, is the tumpline. A tumpline around the head creates a counter moment of force that should reduce the shear force on the lower back. In a military application, the tumpline approach would undoubtedly require a quick release strategy within the helmet. Since this feature would also add weight onto the head, which is already holding up a heavy helmet, then some form of weight-support by the shoulders may also be necessary.

Shoulder carrying. One shoulder-based strategy that emanated from Dr. Rodger Kram's keynote address at this conference was the concept of energy transfer using a dynamic suspension system. In an earlier research paper, Kram (1991) studied springy poles as a compliant suspension system. He found that the sinusoidal motion of the poles was opposite to the person's vertical displacement and, although the energy cost was not different than backpack load carriage, springy poles had less peak pressure and lower loading rates on the shoulders. An added advantage of a dynamic suspension system during walking would be to allow blood flow to enter the shoulder muscles. Blood flow can be occluded from muscle at 14 kPa (Holloway et al., 1976). Most military systems and even newer commercial systems can create shoulder pressures in excess of 20 kPa when loaded with 35 kg loads (Stevenson et al., 1997). Further research is necessary to define how a dynamic suspension system could be designed effectively. The group also questioned when the energy transfer should be returned to the body; in-phase or out-of-phase with marching. Further research is necessary to investigate these factors.

Trunk carrying. Another strategy that was discussed was keeping the load balanced on either side of the trunk. Although balanced (front-back) packs have been studied (Kinoshita at el., 1985; Knapik et al., 1997), this design concept has not been as effective in heat dissipation and from a military operations standpoint. A new concept is to cross only the shoulder straps at the front of the chest. This concept is already used in one shoulder strap handbag and some two-strap mail carrier bags. This design has the advantage of being able to suspend items from it, reduce the problems of pack palsy, and spread the shoulder forces over a larger area but may have disadvantages in restricting breathing or interfering with some military operations. However, it is a good concept and worthy of further investigation.

Waist carrying. Using the pelvic girdle as the primary load carriage site, the workshop group discussed the idea of creating a counter-lever to the pack's weight, thus bringing the pack's centre of mass closer to the body. A cantilever system could be built into the pack by attaching two pivot rods to the lower frame sheet. These cantilevered struts could be lowered to the front of the body providing a place to extend the arms or to hold the rifle. The advantage is a reduction on muscular force needed to balance the pack moment. Although these counter lever struts may sound ideal, they have the negative component of adding additional compressive force to the spinal column. However, this additional compressive force may not become the limiting factor as the spinal column can tolerate large amounts of compression especially if focussed on the pelvic girdle. A definite disadvantage, however, would be additional load on the ankles, knees and hips unless another design feature was built in to compensate for this added load.

Innovative Designs Concepts

New design ideas that have not reached maturity include: the use of exoskeletion, or off-body personally controlled systems. Based on Roger Kram's paper, forms of exoskeletons can be quite beneficial to carrying loads. For example, rhinoceros beetles can carry 300 times their body weight. The concept of using hard outer shells has not been explored in any detail. Off-body strategies such as wheels or guided transport vehicles are also possibilities for future research in personal load carriage. Other areas that require further exploration are modeling the human-pack system so design concepts can be investigated without the exorbitant cost of production and human testing.

Heat Dissipation

One large limiting factor for many good design ideas is the high cost of keeping the body cool. Several excellent design concepts (e.g., front pack and exoskeletons) are thwarted by the fact that approximately 400 watts of power are required just to maintain the human body in temperate conditions. These energy demands would be accentuated during heavy lead carriage situations. Therefore, finding light, cost effective cooling systems is important for soldier load carriage situations. The development of fuel cells is being investigated by many private and military researchers and will be needed to realize certain innovative design concepts.

Conclusions

In conclusion, the working group approached the problem of innovative load carriage design from a conceptual standpoint of mechanical and physiological energy conservation, transfer of forces and moments from the pack to the body and minimizing pack-person interaction forces such as skin contact pressures and body cooling. Ideas of proper training to use load carriage system features and design concepts, such as modularity, are important for a military application. Innovative design concepts such as dynamic suspension systems, exoskeletons and off-body personal guided transport systems were also discussed. It was felt that our understanding of load carriage system design was greatly improved but there are still design concepts and a potential design break through to explore that would ease the burden on the soldier.

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Workshop on Standardization of Load Carriage System Testing

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Workshop Objectives

Recent research initiatives into load carriage and the complexity of implementing new systems in the military need some discussion about the best way to accomplish combined objectives. As the ultimate goal is to provide each soldier with the best possible equipment, and the amount of research needed is so extensive, it makes sense to work together whenever possible. As each country's military requirements are specific, and autonomy of research directions must also be protected, it makes sense to think about the possibilities of standardizing where possible. Hence the purpose of this workshop was to discuss where standardization might be possible and what steps may be needed to accomplish this goal.

Factors Affecting Standardization

The discussion of standardization fell into three topic areas: standardization of the measured variables, standardization of the methodologies, and development of minimum acceptable standards for design specifications. Discussion also centered around sharing of the data pool and discussing the "way ahead".

Participants felt that standardization was a good idea, especially when trying to draw comparisons between findings in the scientific literature and technical reports. Without applying pressure to limit the types of research studies performed, it may be possible to examine already completed research to identify those variables where standardization could occur. For example, load masses and marching speed are known to have a substantial impact on the physiological and biomechanical indicators of performance. Because there are mainly studies that have reproduced these results, it may be possible to develop accurate and reproducible curves to represent the impact of these factors.

This leads to the question of what to measure. From the breadth of the studies within this report, the variables measured ranged from laboratory measures of kinematics and kinetics of gait, aerobic capacity, skin contact pressure, electromyography to performance-based measures of circuits, military tasks, field trials, focus groups and questionnaires. From this conference, it can be seen that scientists are in search of the most critical factors that affect load carriage performance.

The next question is, "How should these data be reported?" Based on the literature and this conference, data can be reported as absolute measures (e.g., maximal oxygen consumption), or normalized by a factor to cross-compare individuals (e.g., body weight) or relative measures taken within an individual (e.g., unloaded or base-line testing condition). Each approach has merit, depending on the individual variable in question.

The next concern was, "What should be standardized?" The literature has often focused on the load mass as a proportion of human characteristics. Although logical, it has been difficult to implement into military doctrine and operations. A second idea is to focus on the test performance outcome measures. For example a standardized testing obstacle course may allow better comparison of different system designs so that studies from different laboratories can be compared during the preliminary stages. Of course the issue of what to measure and how to measure it is also important. The use of questionnaires or discomfort pictograms are also important components as subjective feedback from soldiers remains very critical to the development and selection of an advanced load carriage system.

The advent of standardized testing equipment has been introduced by Canada into load carriage research. Although this approach has been used in many other fields of manufacturing (e.g., chairs, helmets, wheel chair restraint systems), it has not been incorporated into load carriage systems, perhaps because of the complexity of the establishing standards, a small users group, or the perception that there is no safety issue. However, lack of standards can dramatically affect the militaries as they must purchase in large quantities, have difficulty defining the specifications required and have no measurable method for quality assurance. But for performance standards to be put in place using objective tools, it is necessary to ensure that the tools are valid and that the standards are related to soldiers' opinion of discomfort or inadequacy.

The Way Ahead

If standards are to be considered they should be based on scientific data and be related to soldier performance or comfort. The measurement should be valid and repeatable and assess the critical factors of a good and bad system. To develop a NATO STANAG, there must be 'buy-in" from NATO countries, perhaps through a NATO study group. It is possible to examine the International Society of Biomechanics C3D Report on Standards Specifications. If such a standard were to evolve, there would need to be an opportunity and willingness to develop joint assessment strategies and share the data. For the development of minimum standards to proceed, a working group would need to be created and tasked with presenting a proposal to the stakeholders for approval and funding.

Portable Field Measurement Systems Workshop

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Workshop Objective

The objective of this workshop was to discuss design parameters for the ideal portable data monitoring system. The purpose of this would be to provide a quantitative method of analyzing soldier performance in the field.

Portable Measurement System Objectives

The basic objectives identified for a portable system were analysis of operating conditions, soldier stress, fatigue, subjective impressions and the acquiring of kinematics data for biomechanical analysis.

Requirements

Before a portable system can be designed, basic requirements must be quantified. The requirements for a portable system are that it be unobtrusive, light-weight, and relatively low cost. Low cost is required so that multiple soldiers could be equipped at the same time to simplify data runs. A feasible system would also require either telemetry or an on-board data acquisition unit. Finally, the data acquired must meet a certain standard of accuracy, to be identified at a later point, to be acceptable for analysis.

Desired Measurements

Once the basic requirements for the system are determined, the next decision to be made is what types of sensors to place on the soldier. To accomplish this, the precise measurements desired out of the system must be identified. It was discovered that field data are desirable for many different applications and types of data. Suggested measurements ranged from easily accomplished to ones which are presently unmeasurable in field conditions.

Among the more easily measured parameters were EMG, heart rate, thermal (skin and core), posture, position and soldier communications. EMG and heart rate were desired to analyze fatigue and energy expenditure, while temperatures are useful in identifying operating conditions, comfort level and fatigue. Posture monitoring was to be performed to identify soldier activity under load and to track relative fatigue. Operating conditions and general movement could be tracked via Global Positioning System (GPS) sytems. The purpose of monitoring communications from the soldier would be to track mental focus and orders.

Less easily measured parameters, yet possibly achievable, were stress indicators, energy cost and operating conditions. A possible measurement suggested for stress was salivary amylase analysis tests. It was uncertain how precisely this would be administered, however. Energy cost has several standard measurements, including Oxygen Consumption (VO_2) and K4, though no way of performing these in the field was adequately identified. Operating conditions can be estimated through monitoring soldier position on an accurate map, fatigue, meteorological data and gait data obtained through kinematics, but precise data can only be obtained through subjective measures, and then only in a limited scope.

Other measurements that would be desired were identified, however, no way of measuring them was known. These included shear forces on the skin, soldier activity, pace of marching and external forces applied by the backpack on the body. Some of these can be measured in controlled lab conditions, but the sensors used either cannot run unattended or are not robust enough for field conditions.

Modularity

The sheer quantity of data that could be obtained from of a portable system brought up the question of modularity. It was suggested that measurements could be grouped according to purpose and separate tests done for each type. For example, a set of measurements for kinematic data, followed by a set for fatigue, followed by a set of subjective measures could each be performed in separate test runs. The system would then be designed to support each module as it was needed. This method could solve some problems of unit weight and movement restriction by limiting the number of sensors on the body at any one time.

Conclusions

The advantages of a field measurement system make it desirable to pursue. There still remain many questions concerning implementation. Work still needs to be done to create and integrate sensor technologies for field use. Once accomplished, these systems will form an important link between laboratory testing and field trials, allowing cross correlation of variables to be verified in a quantitative manner. All these advantages show that development of a functioning portable field measurement system is a valid and important goal to pursue.

Workshop on System Design and Fabrication Issues

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Workshop Objectives

The main objectives of the workshop were: i) to identify key technical issues requiring clarification or standardization; ii) to review the process of design to determine similarities in current practice among participants; and, iii) to identify areas of common interest for future collaboration.

Technical Issues

The key technical issues that were discussed were control of load distribution in a military context and the practical problems of using a commercial system for military applications. Fabrication problems were also discussed.

Control of load distribution is achievable through current practice in military load carriage system design through a number of strategies. The use of a waist belt and suitable internal frame permits load sharing between the upper and lower body. This allows the user to shift the load during military operations. Since the loads are heavy, distanced carried are long and conditions are often poor, there is a need to provide adjustments of load distribution during use. The most recent research has provided greater insight into the effect of center of gravity location on load carriage performance. But under certain operating conditions, there is a need to minimize relative movement of the load through the use of stabilizer straps.

There are numerous unresolved issues associated with the practical implementation of commercial designs in a military context. For example, the degree of adjustment required and method of action of load lifter straps is not well understood and may result in lack of use or misuse. Although the sternum strap serves a useful function in a civilian context, implementation of sternum straps is difficult given the frontal access requirements for some military activities. Another problem is the need to doff the rucksack quickly, meaning that further design developments are required for current waist belts to be effective in a military context. Many kit items may not be needed in civilian applications, such as NBC equipment or ammunition. The criticality of NBC equipment makes its accessibility a priority at the expense of other more frequently used kit. These differences in functions and use are currently limitations to transferability of civilian pack-based systems to military applications.

In terms of load carriage system fabrication, a number of issues were discussed. Wear may be a concern at sites where one component interacts with a second. For example, the pack shoulder strap actually contacts the load carriage vest in most systems, providing a potential high wear condition in this area. Suitable material choices must be made for these situations. Interference of system components may still lead to pressure "hot spots" for the user. Examples include bar tacks, fasteners, snaps, and seams.

The logistics of procurement and quality assurance for newly designed load carriage systems has not been evaluated. There are critical design, fabrication, and fitting issues that are intrinsic to these systems that need to be identified to ensure that the soldier kit is actually that specified by design teams. Finally, costing should reflect in some way the value of the scientific research used in designing the load carriage system.

For example, the costs of research contracts could be amortized over a number of years and expressed as a number of dollars per system fabricated.

Design Process

The design process identified by the workshop participants had a number of common elements that have made this generation of new load carriage systems more effective. First, all countries had soldier-users involved at an early stage. This involvement assists the design team in understanding the most critical needs of soldiers. Second, design teams were formed that involved continuous iterations and user feedback thus improving communications and acceptance of the final system design. Third, a high level of education at a number of levels was required in order for newly designed systems to perform appropriately. The process of education included: *Issuers* who are often responsible in matters of fitting the soldier and notification of poor quality and repair demands. *Users* since they must understand the principles of operation for system components and learn when and how to continuously adjust load distribution. *Designers* are integrally involved during system development but it is also important that information from issuers and users must be fed back to the design teams. In modern fabrication practices, it is possible to make certain modifications with relatively little cost. The iterative design process used to this point for most load carriage systems should be viewed as on-going once the kit has been issued.

There are specific requirements needed in order to manage quality assurance. There is a need to ensure that all individuals and teams involved in the procurement process fully understand relevant design principles. There is a also a need to perform quality assurance testing on a regular basis both before and after kit is issued.

Areas of Collaboration

The workshop participants agreed that the type of design changes in military load carriage systems are significantly different from past practice. A high level of education is required in order to shift thinking away from the load carriage system as clothing to its role as an integrated part of the soldier system. One of the reasons that new systems have been developed relatively efficiently is through the process of iterative design in teams with continuous user feedback. It was generally agreed that it is essential for the user feedback loop be maintained after issuing these systems and that current unsatisfactory condition reporting methods are not sufficient for this purpose. Participants recommended that regular meetings in which experiences with different military load carriage systems could be examined would provide synergy to the design process in all participating countries.

Physiological, Biomechanical and Medical Aspects of Soldier Load Carriage

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INTRODUCTION

Because of mission requirements or the limited transportation assets of some types of units (e.g., U.S. Army light infantry), soldiers are often required to move their own equipment using load carriage systems. These systems are important for soldier mobility and survivability and if properly designed can minimize performance decrements and fatigue. The carrying of loads by troops is an important aspect of military operations that can become critical in some situations. Overloading of troops and inadequate load-carriage systems can lead to excessive fatigue and impair the ability to fight. Military historians cite numerous examples where heavy loads directly or indirectly resulted in reduced performance, unnecessary deaths, and lost battles (14, 26, 94, 99, 100, 120).

The purpose of this paper is to provide a broad overview of the published research on the historical, physiological, biomechanical, and medical aspects of soldier load carriage. A basic understanding of these topics can assist in the development of appropiate methods to improve soldier mobility.. Practical suggestions are offered for reducing the stress of loads on soldiers by equipment modifications, physical training, and prevention of load carriage-related injuries. Other reviews of similar topics are available (41, 80).

HISTORICAL PERSPECTIVE

Figure 1 shows loads carried by various military units, with emphasis on more recent times. Lothian (93) provides information on a greater number of more ancient military units. Until about the 18th century, troops carried loads that seldom exceeded 15 kg while they marched. Extra equipment and subsistence items were often moved by auxiliary transport including assistants, horses, carts, and camp followers. After the 18th century, auxiliary transport was de-emphasized and more disciplined armies required troops to carry their own loads. Modern soldiers often carried more equipment on the march and less in contact with hostile forces (94).

There have been a number of recorded efforts to study and improve soldier mobility beginning with the British efforts after the Crimean War. These efforts generally focused on either 1) determining an acceptable soldier load based on soldier physical capability and/or operational necessity (1, 4, 15, 94, 120, 136, 137) or developing specialized load carriage systems (1, 72, 94, 120).

In 1987, the U.S. Army Development and Employment Agency (1) proposed five approaches for improving soldier mobility. The first approach was to develop lighter weight components. However, technical developments were expected to reduce loads only by 6% overall (126). The second approach was the soldier load planning model. This was a computer program that aided commanders in tailoring loads through a risk

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analysis based on the mission, enemy, terrain, troops and time (METT-T). The third approach was the development of specialized load-carrying equipment. This included such things as hand carts and all-terrain vehicles. The fourth approach was a reevaluation of current doctrine that might affect load carriage. An example of this was an increased emphasis on marksmanship to reduce ammunition loads. The fifth and final approach was the development of special physical training programs to condition soldiers to develop more physical capability for load carriage.

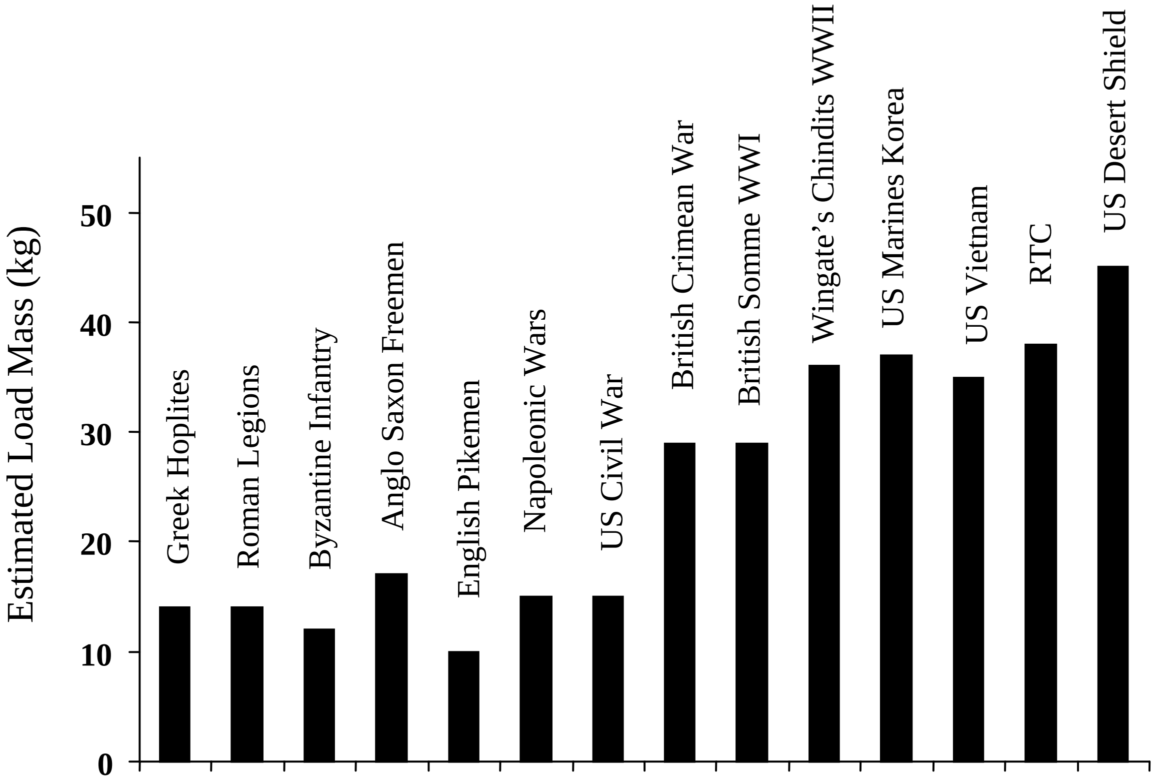

Figure 1. Loads Carried by Various Infantry Units Through History.
JRTC=Joint Readiness Training Center, Ft Chaffee, AR, USA
(References: 25, 61, 69, 93, 117)

Historical changes in soldier physical characteristics may be important (71, 95) because larger soldiers may be able to carry heavier loads by virtue of greater bone and muscle mass (85). It has been estimated that humans have increased their height about 10 cm since the Industrial Revolution, possibly because of better nutrition (29). Table 1 provides a summary of the heights and weights of various groups of soldiers and recruits derived from a variety of sources. Before the Crimean War, only minimum standards are available. U.S. samples show a progressive increase in height and weight since the Civil War, with the increase in weight primarily attributable to an estimated increase in fat-free mass (33).

Table 1. Physical Characteristics of Various Groups of Soldiers and Recruits

	Height (cm)	Body Mass (kg)	Fat Free Mass (kg)[a]	Body Fat (%)[a]
FRENCH SAMPLES				
French (Crimean War)[b]	163	56	NA	NA
French (Post WWI)[b]	163	NA	NA	NA

Table 1 continued on next page

Table 1. Cont'd

	Height (cm)	Body Mass (kg)	Fat Free Mass (kg)[a]	Body Fat (%)[a]
BRITISH SAMPLES				
British (Post WWI)[b]	168	59	NA	NA
British Recruits (1978)[c]	175	70	NA	NA
British Infantry (1976)[c]	175	73	NA	NA
UNITED STATES SAMPLES				
U.S. Soldiers (1864)[e]	171	64	53	16.9
U.S. Soldiers (1919)[e]	172	66	55	15.7
U.S. Soldiers (1946)[e]	174	70	60	14.4
U.S. Male Soldiers (1984)[e]	174	76	63	17.3
U.S. Male Recruits (1986)[f]	175	71	59[g]	15.6[g]
U.S. Male Soldiers 3 groups (1986)[f]	175-176	69-77	58-63[g]	15.9-19.5[g]

NA=Not Available

[a] Estimated from neck and waist girth (142), with exception of last 2 rows

[b] Reference 94

[c] Reference 141

[d] Reference 40

[e] Reference 33

[f] Reference 143

[g] Estimated from skinfolds using equations of Durnin and Womersley (28)

PHYSIOLOGICAL AND BIOMECHANICAL ASPECTS OF LOAD CARRIAGE

Historical information indicates that the problems of load carriage have been with us for a considerable time. Physiological and biomechanical research conducted more recently has resulted in the development of general principles, but studies do not reveal a "best" way of carrying loads that applies to all situations. Improving load distribution across the body, use of combat load carts, and physical training have been demonstrated to improve soldier mobility.

Load Distribution

There are many ways to carry loads, and the technique the soldier will use depends on the characteristics of the load (size, shape, mass, etc.), how far the load may be carried, previous experience, and the equipment available to the soldier (89). Figure 2 illustrates techniques of carrying loads on the upper body that have been directly investigated (5, 8, 20-22, 88, 90, 97).

Backpacks and Double packs. Where the load is carried on the body will affect both energy cost and body mechanics. Loads can be transported with the lowest energy cost (i.e., the most efficient way) when they are carried on the head (55, 97). However, this method is impractical for military operations because it requires a very long training time to use effectively, is useful only in unobstructed horizontal terrain, and produces a high profile (greater body signature).

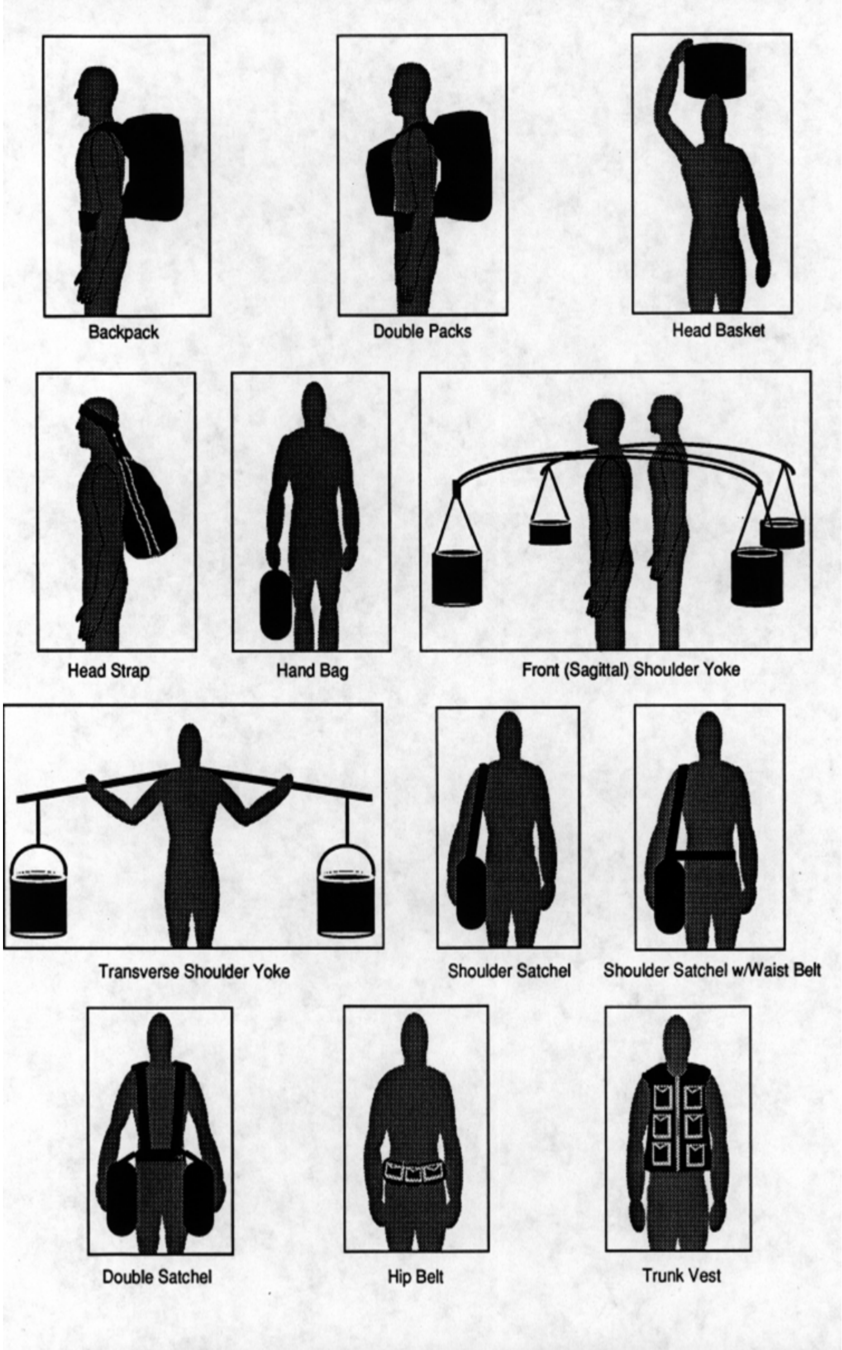

Figure 2. Methods of Load Carriage

A more practical choice for military operations is to carry a load as close as possible to the center of mass of the body (128, 148). In this regard, the backpack and double pack (half the load carried on the front of the body and half on the back) methods have been shown to have a lower energy cost than most other forms of load carriage in many (20, 21, 96, 118) but not all (89) studies. The double pack produces fewer deviations from normal walking than does a backpack, including less forward lean of the trunk (49, 73). With the double pack, increasing load produces a reduction in stride length and increase in stride frequency that is more desirable because it may reduce stress on the bones of the foot. In contrast, stride length becomes longer as backpack loads increase, which could be potentially harmful (49).

Double packs can be useful in some military situations (e.g., medics carrying their aid bags on the front of their bodies) but also imposes major limitations for many military situations. The double pack can inhibit movement and may limit the field of vision in front of the body, making it difficult to see obstructions and traps. They can be burdensome to don and doff; doffing can be very important in situations with sudden or unexpected enemy contact. The double pack can also induce ventilatory impairments (90) and greater heat stress symptoms (64) when compared to the backpack. The double pack may restrict tasks such as firing weapons and donning protective masks.

Designers can take advantage of what has been learned from the double pack by distributing the load more evenly over the torso. Although it may be difficult or almost impossible to make the load equal on the front and back of the body, load carriage systems could allow a part of the load to be moved forward by the use of load-carrying vest and hip belts (see Figure 2). Soldering items included in the frontal load could optimally consist of equipment the soldier may need quickly or may need often. Moving a part of the load to the front would be expected to reduce energy cost, improve body posture, and reduce injuries.

Pack frames and Hip Belts. Pack frames and hip belts reduce shoulder stress. The shoulder straps of a rucksack exert pressure on the skin, which can be measured with transducers under the straps. Shoulder pressure is considerably lower with a pack frame incorporating a wide hip belt compared to a pack frame without a hip belt. In one study, 10 kg carried in a frameless pack resulted in a peak pressure of 203 mm Hg; the same mass carried in a pack with a frame and wide hip belt resulted in a peak pressure of only 15 mm Hg. The pack with the frame and hip belt produced less electromyographic (EMG) activity in the trapezius muscle, also suggesting less stress in the shoulder area (59). There is some suggestion that experienced individuals adjust their walking posture to reduce forces and force fluctuations in the shoulder straps (138).

Subjective reports of discomfort vary, depending on the design of the pack system. For backpacks with and without frames, the majority of discomfort appears to be in the neck and shoulder region. For a backpack with a hip belt, discomfort is localized to the mid trunk and upper legs (90). Overall, when the load is carried primarily on the waist through use of a hip belt, there is less subjective discomfort compared to shoulder load carriage (60).

Placement of the Load in the Backpack. Where the load is placed in the pack will affect both energy cost and body mechanics. Higher energy costs are associated with a load that is lower in the pack and farther away from the body. Lower energy costs are associated with loads placed higher in the pack and closer to the body. This is illustrated in Figure 3. The correlation between energy cost and an index that describes the vertical and horizontal position of the load is 0.85 (107).

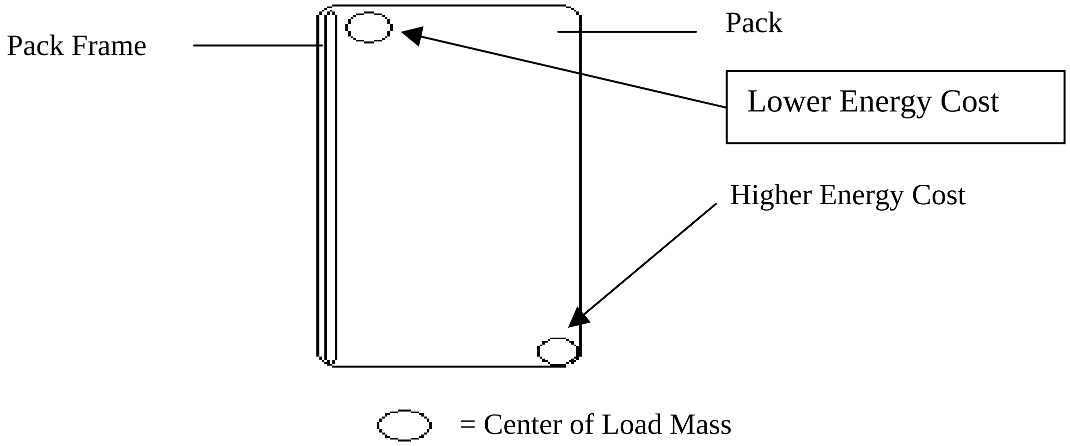

Figure 3. Effect of Placement of the Load in the Backpack on Energy Cost (Reference 107)

Both high and low load placements bring about forward body lean, but this effect is greater for low placements. This is because the lower load is closer to the ankles, requiring more forward body rotation to bring the pack center of mass over the feet (7). The additional forward body rotation tends to bring the body's center of mass over the front half of the foot, which could increase the likelihood of foot strain and injury.

However, placement of the load high in the pack tends to destabilize posture to a greater extent than lower placements, especially among tall men, as measured by the amount of body sway while standing with the load (56). Dynamic moments are about 40% greater with the high-back placement, an affect attributed to the greater rotational inertia of the high load (10).

A low or mid-back load placement might be preferable for stability on uneven terrain, particularly during unexpected stumbles where high-load placement can necessitate relatively high-muscle forces to maintain postural stability. The high load placement may be best for even terrain because it minimizes energy cost and keeps body posture with a load most similar to that without a load (7).

Load Carriage on the Feet, Thighs and in the Hands. Loads can be carried in places other than the torso, although other body positions result in a higher energy expenditure. Loads carried on the feet result in an energy cost five to seven times higher than an equivalent load carried on the upper body (91, 128). For each kilogram added to the foot, the increase in energy expenditure is 7% to 10% (16, 68, 91, 128). This suggests that footwear should be as light as possible, compatible with durability requirements.

Loads carried on the thigh result in energy costs lower than foot carriage but greater than torso carriage. For each kilogram added to the thighs (at about mid-thigh level) the increase in energy cost is about 4% (101, 139). Compared to the feet, less mechanical work is performed when load masses are carried on the thighs because of reduced inertia of the body segments; changes in gait with increasing thigh load are minimal (101).

Carriage of loads in the hands also results in a higher energy cost than torso carriage (21, 96) and produces greater cardiovascular strain (92). Hand carriage is more efficient than foot carriage since the energy cost of carrying loads on the ankles exceeds that of carrying loads in the hands by five to six times if the hand load is carried close to the body (128).

Strap Adjustments. Although not tested experimentally, it is reasonable to assume that shifting loads from one part of the body to another can improve soldier comfort and allow loads to be carried for longer periods of time. Load shifting is accomplished with some pack systems using various strap adjustments. Strap adjustments may redistribute the load to other muscles or other portions of previously loaded muscles. They also allow the skin to “recover” from the pressure of the load.

Some rucksacks have “sternum straps” that are attached horizontally across both shoulder straps at mid-chest level. When the sternum strap is tightened, it pulls the shoulder straps toward the midline of the body and the load on shoulders is shifted in this direction. When the sternum strap is loosened, the shoulder straps move laterally and the load is shifted to more lateral portions of the shoulder.

Most pack systems with hip belts and shoulder straps have adjustments that allow more of the load to be placed on the hips or shoulders. When the shoulder strap tension is reduced (straps loosened), more of the load is placed on the hips. With the shoulder straps tighter, more of the load is placed on the shoulders.

Other strap adjustments that shift load pressures would further improve soldier mobility.

Load Carriage Using Carts

Military personnel seldom consider using carts to transport loads, but for some missions this may be an option. Positive and negative aspects emerged in a field trial of three combat load carts. On the positive side, the tested carts were generally durable, and were effectively used in flat terrain, in barrier construction, and in resupply. On the negative side, the carts created problems in rugged terrain: they were noisy in brush or rocky areas, thus reducing tactical surprise; equipment could get caught in the wheels of some carts (140).

A combat load cart appropriate for military operations should have a low center of gravity, a wide wheel base, and a large wheel size (42, 43). Compared to body carriage, energy cost was reduced by 88% when a 50-kg load was pushed in a cart on a smooth surface (43). Pulled carts (rather than pushed) appear to be easier to control on uneven terrain and also result in considerable energy cost savings (42).

A specially designed combat load cart that was pulled by soldiers using a hip belt resulted in faster march speeds than moving the same loads with a rucksack. Over mixed terrain (paved road, dirt road, field, and rough trail), 34-kg and 61-kg loads were moved 22% and 44% faster over a 3.2-km distance (48). This combat load cart, specifically developed for military operations, is available in the US Army.

Physical Training and Load Carriage

Appropriately designed physical training is another method of increasing soldier mobility. Walking with backpack loads over a period of weeks results in a decrease in the energy cost of carrying the load (134). Australian military recruits with high initial aerobic capacity (predicted $VO_2max=51\ ml\cdot kg^{-1}\cdot min^{-1}$) further improved their aerobic fitness by engaging in regular backpack load carriage. Loads were progressively increased during an 11-week basic training program, and improvements in aerobic capacity were similar to those of a control group performing the traditional recruit training program involving running (124).

Twelve-week physical training programs involving a combination of aerobic training (running) and resistance training (weight lifting), improved the speed at which military men completed a 3.2-km distance carrying 46 kg (87) and military women completed a 5-km distance carrying 19 kg (78) even when these load carriage tasks were not included in the training program. Interestingly, neither running nor resistance training alone improved march speed (87), suggesting that both aerobic capacity and muscle strength must be trained to improve road marching capability. When regular road marching with loads (at least twice a month) was included in a program that also involved running and resistance training, soldiers marched faster than if march training was not included (74). Substantial improvements in load carrying performance were found when civilian women were trained with a combination of resistance training, running, and load carrying (50).

Gender Differences

Compared to men, women walk with shorter stride length and greater stride frequency. As loads increase, the women's stride length decreases while that of the men does not show significant change. With increasing load, women also show a more pronounced linear increase in the time both feet are on the ground (double support time) than do men. Difference between men and women persist even when differences in body size and body composition are taken into account (103).

When men and women were asked to complete a 10-km road march as quickly as possible carrying loads of 18 kg, 27 kg, and 36 kg, men were about 21% faster, regardless of load. On questionnaires, women commented more often than the men that the pack straps were uncomfortable, hip belts ill fitting, and rucksacks unstable. An independent predictor of march time (when gender was included in the equation) was acromial breath (shoulder breadth). Since pack systems have been designed primarily based on the anthropometry of men, these data suggest that if consideration is given to the anthropometry of women in military pack systems, the time gap between men and women may decrease (52, 53).

Factors Involved in the Energy Cost of Load Carriage

Studies conducted on treadmills for short periods of time show that energy cost increases in a systematic manner with increases in body mass, load mass, velocity, and/or grade (9, 11, 39, 130). Type of terrain also influences energy cost, as shown in Figure 4 (42, 110, 129). Pandolf et al. (109) expanded on the work of Givoni and Goldman (38) to develop an equation to predict the energy cost of load carriage:

$$M_W=1.5*W+2.0*(W+L)*(L/W)^2+T*(W+L)*(1.5*V^2+0.35*V*G)$$

Where: M_W = Metabolic Cost of Walking (Watts)
W = Body Mass (kg)
L = Load Mass (kg)
T = Terrain Factor (1.0 = Black Top Road; 1.1 = Dirt Road; 1.2 = Light Brush; 1.5 = Heavy Brush; 1.8 = Swampy Bog; 2.1 = Loose Sand; Snow, dependent on depth of depression (T=1.30+0.082*D, where D=depression depth in cm)(110)
V = Velocity or Walk Rate (m/sec)
G = Slope or Grade (%)

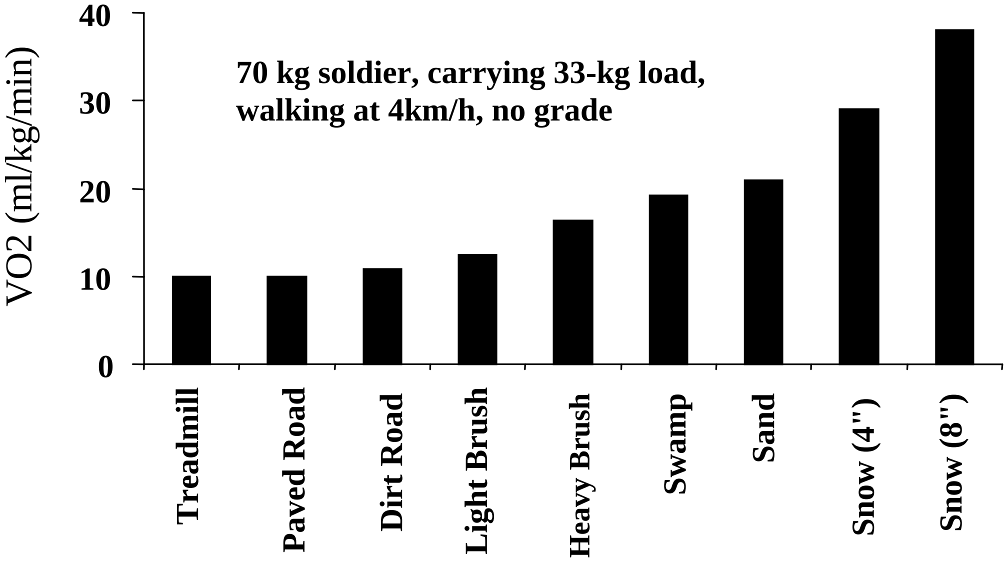

Figure 4. Influence of Terrain on the Estimated Energy Cost of Backpack Load Carriage (References: 109, 110, 129). Numbers after the Snow Estimates are the Depression of the Footwear in the Snow.

The Pandolf equation has been independently validated using a range of loads and body masses (27). However, the equation has several limitations. First, it does not accurately predict the energy cost of downhill walking (115, 116). Downhill walking energy cost approximates a U-shape when plotted against grade: it initially decreases, then begins to increase (98, 145). The lowest energy cost appears to occur between -6% to -15%, depending on individual gait characteristics (145).

A second limitation of the Pandolf equation may be the fact that it may not account for increases in energy cost over time. In studies used to develop the equation, energy cost was examined for short periods, usually less than 30 minutes. Some studies (31, 113) have shown that the energy cost of prolonged (>2 hours) load carriage at a constant speed increased over time at higher loads and/or speeds. Another study did not find an increase in energy cost after about 4 hours of walking (125). There were differences in the type of backpacks used in these studies. The studies showing the increase in energy cost used a pack that place loads primarily on the shoulder; the study not finding the increase in energy cost used a pack with a hip belt that placed much of the load on the hips. Whether energy expenditure increases over time is important because the individual carrying the load may become more easily fatigued if energy cost does increase.

MEDICAL PROBLEMS ASSOCIATED WITH LOAD CARRIAGE

Injuries associated with load carriage, while generally minor, can adversely affect an individual's mobility and thus reduce the effectiveness of an entire unit. Table 2 shows the results of two studies that recorded acute injuries during military road marching operations (76, 123). Foot blisters, back problems, and metatarsalgia were the most common march-related injuries. Table 3 provides a summary of these and other common load carriage related injuries with their signs, symptoms, and prevention measures.

Table 2. Injuries Experienced During Military Road Marches in Two Studies

Table 2a. Injuries Among 335 Infantry Soldier During a 20-Km Maximal Effort Road March (76)

Injury	During March[a]		1-12 Days Post-March (n)[b]	Totals	
	Continued March (n)	Did Not Continue March (n)		N	%
Foot Blisters	16	0	19	35	38
Back Pain/Strain	5	7	9	21	23
Metatarsalgia	1	1	9	11	12
Leg Strain/Pain	0	0	7	7	8
Sprains	1	1	4	6	7
Knee Pain	0	0	4	4	4
Foot Contusion	0	1	1	2	2
Other	1	2	2	5	5
Total	24	12	55	91	100

[a] From medics and physician during the march
[b] From medical records after the march

Table 2b. Injuries Among 218 Infantry Soldiers During a 5-Day, 161-Km Road March (123)

Injury	During March[a]		1-15 Days Post-March (n)[b]	Totals	
	Continued March (n)	Did Not Continue March (n)		N	%
Foot Blisters	43	3	3	49	48
Metatarsalgia	8	2	9	19	19
Back Pain/Strain	4	1	1	6	6
Sprains	2	3	0	5	5
Knee Pain	3	1	3	7	7
Ingrown Toenail	0	3	0	3	3
Stress Fracture	0	1	0	1	1
Other	8	3	1	12	12
Total	68	17	17	102	100

[a] From physician’s assistances at fixed medical sites along the march
[b] From medical records after the march

Table 3. Summary of Common Load Carriage-Related Injuries
With Prevention Stategies (see text for full descriptions)

INJURY	SIGNS AND SYMPTOMS	PREVENTION
Foot Blisters	Elevated area, lighter in color than surrounding skin, filled with fluid. Pain, burning, warmth, erythema	1. Acrylic, nylon, or polyester inner sock; thick, snug, dense weave outer sock with inner sock 2. Spenco insoles 3. Antiperspirants 4. Load distribution more evenly around body center of mass 5. Reduce load mass 6. Pre-condition feet through physical training and road march practice 7. Improve aerobic fitness 8. Smoking/tobacco cessation
Low-Back Pain	Pain, muscle spasm, neurological symptoms	1. Load distribution more evenly around body center of mass 2. Reduce load mass 3. Trunk and abdominal strengthening and stretching
Metatarsalgia	Pain, swelling on sole of foot	1. Pre-condition feet through physical training and road march practice 2. Reduce load mass
Stress Fractures	Persistent, boney pain	1. Smoking/tobacco cessation 2. Pre-condition feet and legs through progressive physical training and road march practice
Knee Pain	Pain, swelling, crepitus, instability	Lower extremity strengthening and stretching
Rucksack Palsy	Upper extremity numbness, paralysis, cramping; scapular winging	Framed rucksack with use of hip belt on rucksack

Foot Blisters

Foot blisters are the most common load carriage-related injury (17, 76, 104, 123). Blister can occur when slight movements of the foot in the footwear produce shear forces on the skin. Some portions of the footwear exert more pressure on the skin than other portions. If the foot movements produce enough shear cycles at these pressure points, and if the pressure is great enough, a blister will result (84). Blisters can cause extreme discomfort, may prevent soldiers from completing marches, and can lead to many days of limited activity (2, 76, 104, 119, 123). Especially in field conditions, if blisters are not properly managed, they can progress to more serious problems such as cellulitis or sepsis (2, 58).

Heavy loads have been shown to increase blister incidence (52, 75, 122), possibly by increasing pressure on the skin and causing more movement of the foot inside the boot through higher propulsive and breaking forces (73). Other blister risk factors include tobacco use, low aerobic fitness, and ethnicity (82, 83, 123).

When loads are very heavy (61 kg), the double pack has been shown to result in less likelihood of blisters than the backpack (77), suggesting that better load distribution can reduce blisters. Spenco shoe insoles have also been shown to reduce foot blister incidence, possibly because they absorb some frictional forces in anteroposterior and mediolateral directions (127, 131, 132). Regular physical training with load carriage may induce skin adaptations that reduce the probability of blisters (84). Blisters may thus be less of a problem in units that march regularly; however, sudden increases in march intensity or distance will probably make blisters more likely, regardless of training regularity.

Moist skin increases frictional forces and probably increases blister incidence (2, 84, 105). Acrylic socks decrease the number and size of blisters among runners (57), possibly by conducting sweat away from the foot (32). A nylon sock worn inside a wool sock reduces the incidence of blisters among soldiers who are road marching (3, 146). A polyester sock worn inside a very thick wool-polypropylene sock reduced blister incidence during Marine recruit training (79). It is reasonable to assume that changing wet socks for dry ones may also reduce foot blisters.

Antiperspirants also reduce foot sweating (19, 70). A 20% solution of aluminum chloride hexahydrate in an anhydrous ethyl alcohol base is effective in reducing the likelihood of march-related blisters if the preparation is applied to the entire foot for at least three nights before a march (81). Once the antiperspirant effect has been achieved, it may be maintained with applications once per week (12). However, many individuals report irritant dermatitis using this preparation (81), which may require the application of a topical steroid. Possible ways or reducing irritant dermatitis include using a lower concentration preparation, changing the treatment schedule (same number of applications but over a longer period of time), or discontinuing use. Antiperspirants in emollient bases are not effective in reducing blisters, presumably because emollients interfere with the antiperspirant effect (121).

Low Back Injuries

Low back injuries can pose a significant problem during load carriage. Low back injuries are difficult to define because the pain may result from trauma to a variety of structures including spinal discs, the ligaments connecting the vertebral bodies, nerve roots, or supporting musculature (67). In one study (76), 50% of the soldiers who were unable to complete a strenuous 20-km walk reported problems associated with the back. Dalen et al. (18) reported frequent problems with back strains during a 20 to 26-km walk. However, Reynolds et al. reported only a 3% low-back injury incidence and few associated days of limited duty after a 161-km road march.

Heavy loads may be a risk factor for back injuries (122). This could be because heavier loads lead to changes in trunk angle muscles (44, 47, 106, 111) that can stress back, or because heavier loads do not move in synchrony with the trunk (106, 114) causing cyclic stress of the back muscles, ligaments, and the spine (47, 106). It has been suggested that the double pack may help reduce the incidence of back problems because it results in a more normal posture and eliminates prolonged bending of the back (73). Thus, better load distribution could reduce back injuries. Also, a general overall strengthening and warm-up program involving the back, abdomen, hamstrings, and hip muscles may assist in prevention of back injuries (67).

Metatarsalgia

Metatarsalgia is a descriptive term for nonspecific painful overuse injury of the foot. The usual symptom is localized tenderness on the sole of the foot under the second or third metatarsal head. Sutton (133) reported a 20% incidence of metatarsalgia during a strenuous 7-month Airborne Ranger physical training program that included regular load carriage. One study (76) reported a 3% incidence after a single strenuous 20-km walk with soldiers carrying 45 kg. Another study reported a 9% incidence following a 5-day, 161-km road march with soldiers carrying an average (SD) 47±5 kg (123).

Metatarsalgia is sometimes associated with foot strain caused by rapid changes in the intensity of weight-bearing activity (67). Walking with heavy loads may be a predisposing factor for metatarsalgia since this may cause the foot to rotate anterio-posteriorly around the distal ends of the metatarsal bones for more prolonged periods of time, resulting in more mechanical stress in this area (73).

Stress Fractures

Lower extremity stress fractures are common in military recruits (13, 30, 36, 37, 65, 66) and have also been reported in trained soldiers (66). During the Central Burma campaign in WWII, 60 stress fracture cases were reported in one infantry unit during a 483-km road march (24).

Stress fractures are attributable to repetitive overloading of bones during activities such as road marching. The most common areas of involvement are the metatarsals of the feet (24), although many other lower extremity sites can be involved (66). When the metatarsals are involved, tenderness is generally localized on the dorsal side of the metatarsal shafts, which distinguishes the pain from metatarsalgia. Other common stress fracture areas include the tibia (46) and fibula of the leg (45). Under similar training conditions, here may be gender differences in the anatomic location of stress fractures, with men experiencing proportionally more stress fractures in the foot and women experiencing more in the hips, pelvis and legs (Unpublished data, Ft Jackson, SC).

Demonstrated risk factors for stress fractures include female gender (13, 66), white ethnicity, older age (13), taller body stature (37), prior physical inactivity (35, 37), and smoking (34). Other factors that may increase risk include load-carriage distance (62, 66) and walking style (37, 108).

Knee Pain

Knee pain is another condition that has been associated with load carriage. Dalen et al. (18) reported a 15% incidence (17 cases of 114) of knee pain during their load-carriage study. Knapik et al. (76) reported only a 1% incidence of knee pain (2 cases from 335 soldiers) following a 20-km march, but the two cases resulted in a total of 14 days of disability. Reynolds et al. (123) found a 3% incidence of knee pain (7 cases from 218 soldiers) following a 161-km march**.**

Various disorders that may be involved in knee pain include patellofemoral pain syndrome, patellar tendinitis, bursitis, and ligamentous strain. These conditions can arise from an abrupt increase in road marching mileage or intensity or from climbing hills if soldiers have not been conditioned for this. Quadriceps and hamstring strengthening and stretching exercises, along with heel cord stretching, are important for the prevention of recurrence (144).

Rucksack Palsy

Rucksack palsy is a disabling injury and has been widely reported in association with load carriage (6, 23, 54, 63, 133, 147). It is hypothesized that the shoulder straps of a backpack can cause a traction injury of the C5 and C6 nerve roots of the upper brachial plexus. In minor cases, compression results in entrapment of the long thoracic nerve. Symptoms include numbness, paralysis, cramping and minor pain in the shoulder girdle, elbow flexors, and wrist extensors. Long thoracic nerve injuries usually present with "scapular winging" because of weakness of the serratus anterior muscle. Sensorimotor deficits from rucksack palsy injuries are usually temporary but in some cases, may result in a chronic condition. Nerve conduction studies and EMG studies may be necessary to document this condition (6, 147).

Use of a frame and hip belt has been demonstrated to reduce the incidence of rucksack palsy (6), presumably by reducing pressure on the shoulders (59). Hypothetical risk factors for rucksack palsy include heavy loads, load distribution, and longer carriage distances (6, 122).

LOAD CARRIAGE & PERFORMANCE OF OTHER TASKS

A significant consideration from a military perspective is how well soldiers are able to perform military tasks during load carriage. Load mass, load volume, and load distribution appear to be important variables. As the mass increases, there are systematic decrements in the performance of tasks such as longer runs, short sprints, agility runs, ladder climbs, and obstacle courses (51, 60, 102). The decrement in performance of some tasks is estimated at about 1% per kilogram load (60). Loads of greater volume inhibit movement under obstacles. The distribution of the load within the backpack can also influence performance of specific tasks (60). Gender differences in load carriage are also apparent with women having more difficulty than men in climbing walls (presumably due to shorter stature and lower muscle strength) and women less accurate than men in throwing grenades (51).

In some operations, soldiers are required to walk long distances and perform critical military tasks at the completion of the march. Very strenuous marches (maximal speed with loads of 34 to 61 kg over 10- to 20-km distances) lead to post-march decrements in marksmanship and grenade throw distance (52, 75, 77, 86). The decrements in marksmanship are presumably attributable to small movements of the rifle resulting from fatigue of the upper body muscle groups, fatigue-induced tremors, or elevated heart rate or respiration (75, 86, 135). Marksmanship decrements last for only short periods of time (77). The decrements in grenade throw distance may be due to a nerve entrapment syndrome (6, 147) or pain in the shoulder area, both resulting from the pressure of the rucksack straps. Lower body muscular power (as measured by the vertical jump and Wingate test) and muscle strength do not appear to be adversely affected by prolonged pack load carriage (52, 75, 86, 112).

CONCLUSIONS: IMPROVING SOLDIER MOBILITY

This review suggests many ways of facilitating soldier mobility including load reductions, load redistribution, equipment modifications, and physical training. Load reductions can be accomplished by tailoring the load to the specific operations and by using special load-handling devices. Commanders must make realistic risk analyses and take only the equipment necessary for the mission. Special combat load carts are available that could be useful in special situations such as marches on unobstructed terrain or in close resupply operations (1, 48). Reducing loads will lower energy cost, increase soldier comfort, and may reduce some types of injuries, especially blisters, back problems, and metatarsalgia.

Equipment modifications should first focus on redistributing the load about the center of mass of the body. Many military carriage systems have vests and belts that have pockets and attachment points useful for moving some items from the rucksack to the front of the body. Items carried on the front of the body should be those likely to be needed suddenly or needed often. Pack frames and well-padded hip belts provide several benefits including reducing loads on the shoulder, great comfort for the shoulder, and a possible reduction of some types of injuries. Frames and hip belts may improve soldiers' performance on tasks requiring the use of the upper body. Load shifting through the use of belts and buckles (e.g., sternum straps to move loads to different points on the shoulder) may also be helpful. The optimal distribution of the center of mass of load within the rucksack may depend on the type of terrain. On roads or well graded paths, placement of heavy items high in the pack is preferable to lower energy cost, maintain a more upright body posture, and possibly reduce low back problems. On uneven terrain a more even distribution of the load within the pack may be more helpful to maintain stability.

Regular physical training that includes aerobic exercise, resistance exercise, and road marching can improve load carriage performance. Road marching should be conducted at least twice a month with loads that soldiers are expected to carry in unit operations. Loads and distances should be increased gradually over sessions until a maintenance level has been achieved. New unit members should be given time to adapt through the same gradual program. Regular physical training has been shown to increase march performance and may reduce some types of injuries.

It is desirable to reduce load-carriage-related injuries that impair performance, cause discomfort and disability, and result in a loss of manpower. Blister incidence can be reduced by keeping the feet dry and this may be accomplished by 1) the use of an polyester inner socks combined with wool or wool-polypropylene outer socks, 2) antiperspirants applied at least three days prior to a march and reapplied at least once a week, and 3) frequent sock changes. Spenco insoles and distributing the load more evenly around the torso may also reduce blister incidence. Aerobic physical training combined with regular load carriage marches may reduce the incidence of stress fractures and blisters. The use of frames and hip belts can reduce the incidence of rucksack palsy.

Soldier mobility can be improved by lightening loads, improving equipment and load distribution, appropriate physical training, and specific techniques directed at injury prevention. Suitable changes will allow soldiers to complete missions at lower energy costs, with more comfort, and with fewer injuries.

DISCLAIMERS

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Physiological Strain During Load Carrying: Effects of Mass and Type of Backpack

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Summary

The effects of mass (0, 5.4, 10.4 kg) and the type of support (on the shoulder or on waist) on physiological and mechanical strain indices of four young male subjects were quantified. While standing, oxygen uptake was not influenced by the type or mass of the backpack, and averaged 10% maximal oxygen uptake. The heart rate increased significantly by 9 beats per min while standing wearing a backpack. While walking ($1.33\ m{\cdot}s^{-1}$) the mass significantly influenced both the heart rate and the oxygen uptake carried, but both types of strain remained below the tolerance limits for prolonged wear. Standing supporting a load did not significantly increase the EMG signal of the trapezius shoulder muscle (pars descenders). While walking, load carrying significantly increased the EMG of the shoulder muscles. The pressure on the skin under the shoulder straps during load carrying on the shoulders was more than a factor of three times higher than the threshold value for skin and tissue irritation. Load transfer to the waist with a flexible frame reduced the pressures on the skin of the shoulder to far below the threshold value. On basis of these results it was concluded that even with relatively low loads the limiting factor was the pressure on the skin, if a waist belt did not relieve such pressure on the shoulders.

Introduction

The main goal in most of the studies concerning backpacking has been to determine the energy cost of walking taking into account a variety of terrains (grade and surface), velocities, and external loads (Datta and Ramanathan 1971; Goldman and Iampietro 1962; Legg and Mahanty 1986; Myles and Saunders 1979; Pandolf et al. 1976, Pandolf et al. 1977, Pimental and Pandolf 1979, Soule et al. 1978) or to determine the level of metabolism, expressed as a percentage of maximal oxygen uptake (Vo_2max) which could be maintained without physical fatigue (Epstein et al. 1988; Shoenfield et al. 1977; Evans et al. 1980). A few studies have examined the effects of load-carrying on muscle activity (Cook and Neumann 1987; Bobet and Norman 1982), walking kinematics (Bloom and Woodhull-McNeal 1987; Martin and Nelson 1986), or the effects of load distribution on loss of mobility (Holewijn and Lotens 1992).

In this paper the effects of the mode of carrying and the load mass were investigated by simultaneous measurement of several physiological strain parameters. Firstly, from a study of the literature different types of strain were identified which could limit the endurance time of walking with a backpack (Holewijn 1986). It was found that besides a reduction in physical performance, effects on the metabolic, musculo-skeletal, and cardiovascular systems, and the skin underneath the shoulder straps are important. The aim of this study was to quantify all the resulting strains to assess the limiting factor in the endurance time of walking with a normally loaded backpack. It was hypothesized that local strain of the shoulder muscles or pressure on the skin under the shoulder straps could be the cause of frequent complaints during backpacking. Therefore, the load on the shoulder muscles was estimated with electromyographic techniques (EMG) and the pressure on the skin of the shoulder region was measured at several locations under the right shoulder strap to assess the distribution of pressure. The oxygen uptake (Vo_2) and the heart rate were also monitored to exclude the possibility that these strains were above the limits of tolerance.

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Methods

Subjects. Four healthy young male students participated in this study. They all participated regularly in physical activities but were not used to carrying backpacks. The subjects were informed of the purpose and procedures of the study and consented to participate. The subjects had a mean age of 24 years (range 23-26), mass of 75.1 kg (range 69-81.5) and Vo_2max of 3.4 $l \cdot min^{-1}$ (range 3.3-3.8).

Two packs were used in this study. One was the backpack in use in the Royal Netherlands Army (Mil), as pack mounted high on the back by straps. The straps ran from the front of the waist belt to the back being attached to the pack on the same side and crossing between the shoulder blades to reach the waist belt on the opposite side. On the shoulders the straps had a width of 5 cm and were of heavy canvas (Figure 1a). This type of backpack puts the load mainly on the shoulders. The second backpack was a custom-made pack (Cust) where most of the load was supported on the hips by means of a flexible frame connected to a padded 10-cm wide waist belt (Figure 1b). The padded shoulder straps were 8 cm wide on the shoulders.

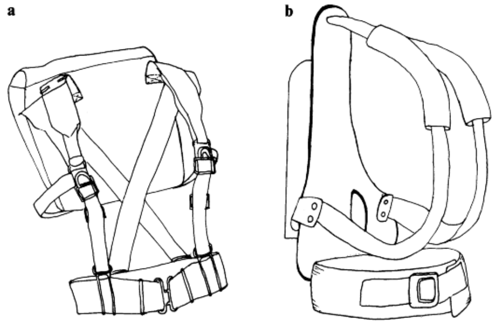


Figure 1. The two different types of backpacks used in this experiment.
The small military backpack (a) hanging on the shoulders and the custom built pack (b)
with a flexible frame, transferring the load on the hips.

Loads of 5.4 kg and 10.4 kg were chosen, representing the fighting and marching order of a Royal Netherlands Army soldier, respectively. These loads were applied both while standing and walking on a treadmill at a moderate walking speed of 1.33 $m \cdot s^{-1}$. Measurements without a pack served as control.

Physiological measurements and apparatus. The EMG activity of the descending part of the right trapezius muscle was measured with two surface silver-silver chloride electrodes (PPG, Hellige), positioned on the distal third of the muscle with an inter-electrode distance of 2 cm parallel to the muscle fibres. The electrodes were attached after thoroughly cleaning the skin with alcohol. The reference electrode was attached on the acromion. The EMG recordings started 1h after application of the electrodes because by that time the skin impedance had almost stabilised (Zipp et al. 1977).

The EMG signals were first passed through a small battery fed preamplifier (100x), mounted on a waist belt, and then through an amplifier with a gain of 2 x -50 x and a band filter of 5-1,000 Hz (slopes: low pass filter 6 $dB \cdot octave^{-1}$; high pass filter 12 $dB \cdot octave^{-1}$). The EMG was then sampled over 1 min periods by a microcomputer (IBM, USA) using a 12 bit A/D board (DT2821, Data Translation, USA) set at a sample frequency of 2,048 Hz, and stored on a hard disk. The root mean square value (RMS) of the amplitude was determined on line with a custom built (RMS) detector (AD 637, time constant = 55 ms) and sampled with the same equipment.

Post experimental analysis of the EMG consisted of dc-correction with a data analysis software package (Asystant, Macmillan Software Company, USA). From every EMG recording four samples of 1 s duration, equally distributed over the 1 min sample period were taken. The RMS data of these four samples were transformed to force values using a previously determined RMS versus force relationship. This calibration curve between RMS of the EMG of the trapezius muscle and the force produced by this muscle was determined for each subject with two adjustable slings running over the shoulders, one of which was connected to a floor mounted force transducer (Z 2H6, Hottinger Baldwin Messtechnik). The shoulder was positioned directly above the force transducer. The subject performed three isometric maximal voluntary contractions (MVC), with a 10 min rest period between each contraction, by lifting the shoulders, while sitting with a straight back and with the feet not touching the floor. This posture was chosen to ensure that the force could only be produced by lifting the shoulders and not by other means (leg muscles, leaning forward). The highest force level maintained for 3 s was taken as the MVC. After 30-min rest the RMS value was measured for l s at force levels of 5%, 10%, 20%, 30%, 50%, and 100% MVC. Between each measurement there was a 10-min rest. By power regression a curve was fitted to the data.

The pressure under the shoulder strap on the skin of the right shoulder was measured with a miniature pressure transducer (model 156, Precision Measurement Company, USA) measuring 8.5 x 4 mm and 1 mm thick. The small dimensions made it possible to measure the pressure with a minimal change to the curvature of the shoulder strap thereby introducing a negligible artifact in the recordings. The pressure signal was amplified (MG 3150, Hottinger Baldwin Messtechnik, FRG) and sampled by an IBM microcomputer with a sample frequency of 2,048 Hz and stored on disk. While the subjects were standing the pressure on the skin was measured at five positions under the right shoulder strap and for each position at three locations, i.e. the lateral and the medial edge of the strap and in the middle. The five positions were spaced out equally over the shoulder strap at intervals of 5 cm, position 3 being just on top of the shoulder. During walking the skin pressure was measured only at position 3 on the medial edge of the shoulder strap.

The Vo_2 ($l^{\cdot}\ min^{-1}$) was measured with an Oxylog portable system (Morgan Ltd. England) which was mounted on a fixed frame above a treadmill. The Vo_2 ($l^{\cdot}\ min^{-1}$) was normalised with respect to each subject's Vo_2max and with respect to the total load (mass of the subject + load). The Vo_2max was estimated during a submaximal treadmill running test, by increasing the running speed at 3% gradient until a heart rate of 160 $beats^{\cdot}\ min^{-1}$ was reached. The Vo_2max was calculated by extrapolating the subject's heart rate versus Vo_2 relationship to his maximal estimated heart rate (Astrand and Rodahl 1986). This method had the advantage that the subjects were not stressed to their limits, but the accuracy was 10%-15% less than a direct measurement of Vo_2max (Davies 1968).

The heart rate was monitored continuously by a custom-built cardiotachometer with a charcoal electrode set (Respironics, USA) mounted on the chest.

Experimental procedure. Before the load-carrying sessions, each subject's Vo_2max was estimated, followed by the measurement of the force versus RMS calibration curve. After a rest period of 30 min the load carrying sessions started. Each carrying session consisted consecutively of 20-min standing, 10-min rest and 20-min walking on the treadmill at a velocity of 1.33 $m^{\cdot}s^{-1}$.

While standing and walking the oxygen uptake and heart rate were recorded continuously on a chart recorder. Both while standing and walking the pressure, the EMG and the RMS were measured at the 1st, 10th, and 20th min. Off-line, the average EMG and RMS values were calculated for each l-min measurement period. This cycle was repeated five times, with a 20-min rest between each cycle. The five carrying conditions (no backpack, Military and the Custom built backpacks, each with a 5.4 and 10.4 kg load) were administered according to a balanced design.

Statistics. The data were assessed by analysis of variance (ANOVA) with the Systat computer programme (Systat Inc. USA) after checking normality of the data (Kolmogorov-Smirnov test) and the homogeneity of variance. If significant F values were found ($P<0.05$) the differences between levels within an effect were analysed for significance by a Newman Keuls post hoc test ($P< 0.05$).

Results

Oxygen uptake

There were no significant differences found in metabolism of the 1st, 10th, and 20th min in any of the carrying sessions. Therefore, the data were averaged over the three measuring points. In Figure 2 the effect of the type of backpack on the relative metabolic strain is shown. During standing the metabolic strain was not significantly influenced by the load and averaged 340 ml · min^{-1} (10% Vo$_2$max). However, during walking differences between loads were evident. Compared to standing, walking with the 5.4-kg load caused a significant increase of the oxygen uptake of 620 ml · min^{-1} (1.5% Vo$_2$max) and with the 10.4 kg load the increase was 740 ml · min^{-1} (4.8% Vo$_2$max).

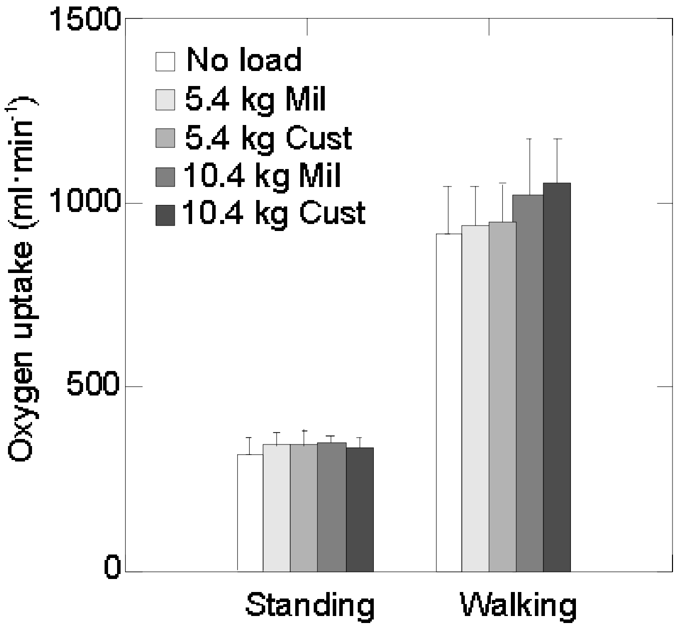


Figure 2. The effect of different combinations of load and backpack type on the metabolic strain (oxygen uptake, ml · min^{-1}), while standing and walking (speed = 1.33 m · s $^{-1}$). Mil, Military backpack; Cust, custom built backpack.

No significant difference was found between the two types of backpack. Comparing the oxygen uptake for the two different loads, the energy cost necessary for displacement of body mass and load separately can be calculated. The average energy cost during walking without a load amounted 4.2 W· kg^{-1} of body mass. However, the average energy cost per kg load at first decreased (1.1 W·kg^{-1} for the first 5.4 kg backpack mass) but then increased (6.3 W· kg^{-1} for the next 5 kg of backpack mass) with increasing loads. The average energy cost per kg load for the first 5 kg was thus lower than for a kg of body mass, but increased steeply with increasing loads.

Heart rate

During standing the average heart rate increased significantly by 9 beats· min^{-1} with load carrying. There was no significant difference between the four load carrying conditions (Figure 3). During walking the heart rates during control measurements remained significantly lower than the heart rates during the load-carrying conditions (Figure 3).

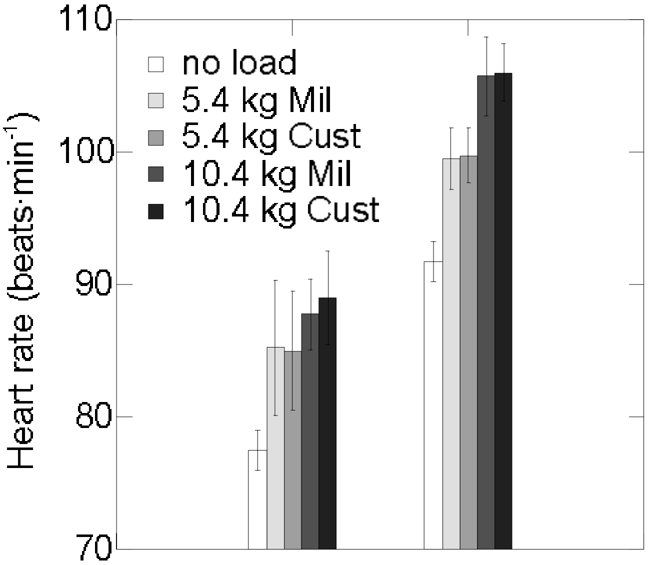


Figure 3. The effect of different combinations of load and backpack type on the heart rate (mean and SD) while standing and walking (speed=1.33 m·s^{-1}). Mil=Military backpack; Cust=custom-built backpack

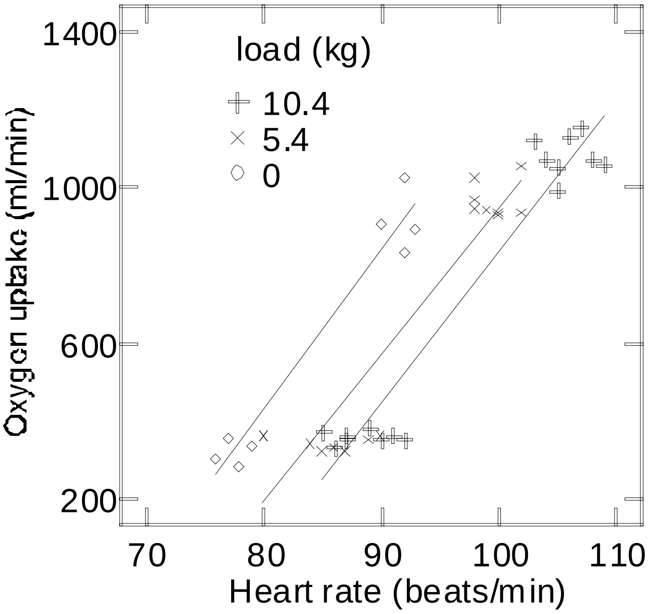


Figure 4. The effect of different loads on the relationship between the heart rate (beats · min^{-1}) and oxygen uptake (ml · min^{-1}) while standing and walking (speed=1.33 m·s^{-1}).

Electromyographic activity of the trapezius muscle amplitude

The statistical analysis revealed that there was no significant change in RMS over time. In further analyses the three measurements were averaged. Converting RMS values of the EMG of the trapezius muscle to force values resulted in the force levels shown in Figure 5.

Although the force level while standing showed an increase when they carried a load, the effect was not significant. The force averaged 5.4 N. While walking the force levels increased significantly during load carrying, but not in the control situation. The custom-built backpack with a 5.4 and 10.4 kg load and the

Military backpack with the 5.4 kg load resulted in similar force levels of 15 N (1.6% Maximal Voluntary Contraction, MVC), 17 N (1.7% MVC), and 19 N (1.9% MVC), respectively.

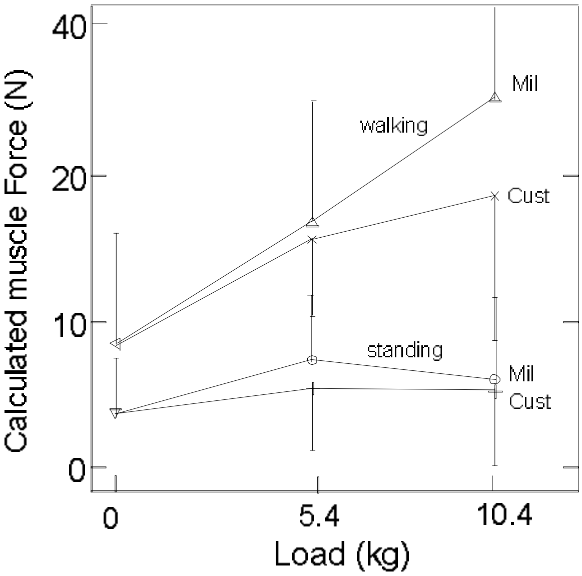


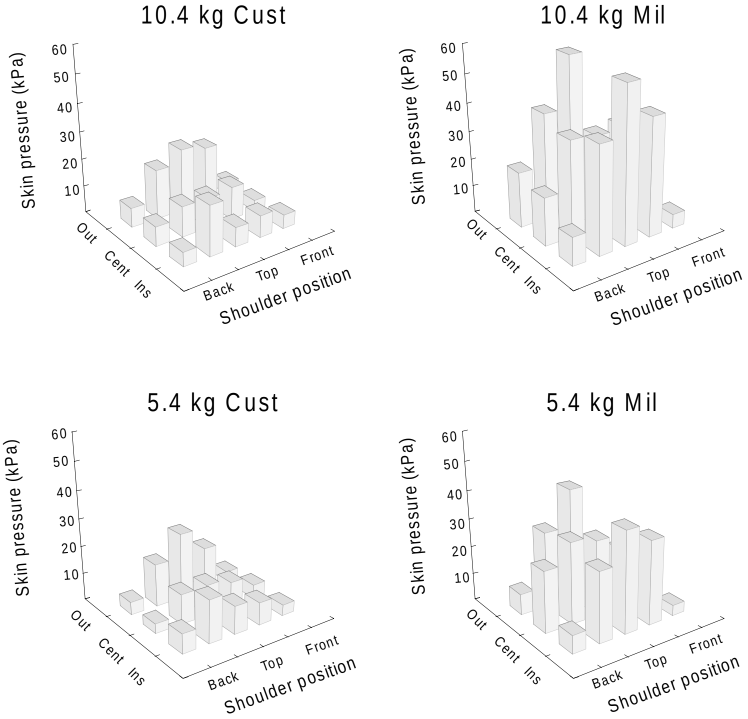
Figure 5. The calculated force level (N, mean and SD) of the descending part of the trapezius muscle while standing and walking without a load and using two types of backpack carrying 5.4- and 10.4 kg loads. Mil, Military backpack; Cust, custom built backpack

The Military backpack, however, containing a 10.4-kg load resulted in a force level of 25 N (2.7% MVC), which was significantly higher than in the other three load conditions. The force level was significantly dependent on the subject, in particular for the heavy load. This explains in part the variation in force level. With the Military backpack the increase in force, comparing standing and walking, was significantly higher than with Custom-built backpack.

Pressure of the shoulder straps on the skin

While standing the pressure distribution on the skin under the right shoulder strap measured in each of the 15 sites is graphically represented in Figure 6, showing the differences between the two backpacks and the effect of increasing the load. The two backpacks induced a pressure increasing from the back at the lower edge of the scapula to the top of the shoulder and a sharp decrease on the front side of the shoulder. Carrying the loads using the Military backpack caused a peak pressure on the acromion (top of the shoulder outerside) and another on the upper edge of trapezius muscle (top of the shoulder, innerside).

The former peak was also found using the Custom-built backpack, but smaller in amplitude. The peak pressure on the medial side was not present with Custom built backpack. The peak skin pressures using the Military backpack were significantly higher than the skin pressures using Custom-built version.
The maximal pressures amounted to 20 kPa (150 mm Hg) (Military backpack, 5.4 kg), 27 kPa (203 mm Hg) (Military backpack, 10.4 kg), 2 kPa (15 mm Hg) (Custom built backpack, 5.4 kg and 10.4 kg).


10.4 kg Cust

10.4 kg Mil

5.4 kg Cust

5.4 kg Mil

Figure 6. The distribution of average skin pressure of the right shoulder measured at five positions under the shoulder strap (from back to front side) while standing carrying two different loads and using two types of backpack. For each position the pressure was measured in the middle of the strap (cent) and at the inner side (Ins) and outside (Out.).

At most positions the pressure on the edges of the shoulder strap was higher than in the middle of the strap. The statistical analysis showed further that increasing the load from 5.4 to 10.4 kg in the Military backpack caused a significant increase in the skin pressure of 36%, whereas no significant effect was found with Custom-built versions. The form of the pressure distribution did not appear to be significantly influenced by the load level.

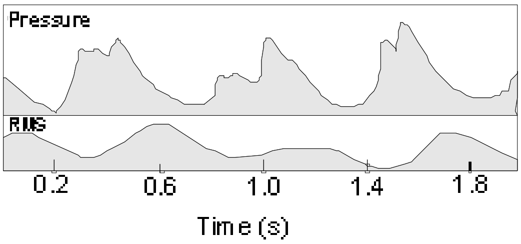


Figure 7. A typical example of the sinusoidal variations of the skin pressure and root mean square (RMS) of the electromyogram of the trapezius pars descendens muscle while walking (speed = 1.33 $m \cdot s^{-1}$) using the military backpack with a load of 5.4 kg.

While walking the pressure showed sinusoidal fluctuations about 0.2 s out of phase with RMS of the EMG of the trapezius muscle (Figure 7). Similar to measurements made while standing, the skin pressure while walking was significantly dependent on mass and the type of backpack (Figure 8).

The Custom built backpack had a statistically significantly lower skin pressure on the top of the shoulder than the Military backpack. Further, the skin pressure using the Military backpack increased significantly with an increase in the load from 5.4 kg to 10.4 kg.

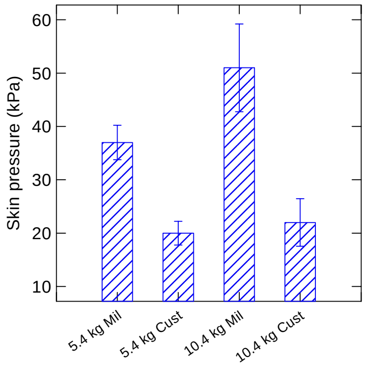


Figure 8. The skin pressure (mean ! SD) on the top of the shoulder while walking using two types of backpack and carrying two different loads. Mil, Military backpack; Cust, custom built backpack

Discussion

Metabolic and cardiovascular strain

In this study, in contrast to other studies, it was found that carrying a backpack had a significant effect on the heart rate while standing (Borghols et al. 1978; Pierrynowski et al. 1981; Pimental and Pandolf 1979). A possible explanation may be that in this study the time taken standing was more than a factor of two longer than in other studies and in combination with a different type of backpack this may have resulted in significant effects on the cardiovascular system. This increase in heart rate has been commonly observed during static muscular exercise. Kilbom (1976) has concluded in her review that the resulting increase in cardiac output during static contractions is mainly directed towards the peripheral parts of the body and only a small part is supplied to the myocardium. In this study standing while carrying a backpack, however, required no significant extra metabolic energy which is in agreement with other studies (Borghols et al. 1978; Pierrynowski et al. 1981). Thus, the relationship normally found between heart rate and the oxygen uptake during dynamic exercise was disrupted during static contractions, as can be seen in Figure 4 .

In most studies it has been assumed that the metabolic cost per kg load is independent of the total mass for loads carried centrally on the body (Goldman and Iampietro 1962; Datta et al. 1973; Myles and Saunders 1979; Pierrynowski et al. 1981; Pimental and Pandolf 1979; Soule et al. 1978). However, according to our data the average energy cost per kg added weight is not constant. During walking without a load the energy cost amounted 4.2 $W \cdot kg^{-1}$ of body mass. During weight carrying, the average energy cost per kg load at first decreased (1.1 $W \cdot kg^{-1}$ for the first 5.4 kg load) but then increased (6.3 $W \cdot kg^{-1}$ for the next 5 kg load) with increasing loads. The average energy cost per kg load for the first 5 kg was thus lower than for a kg of body mass, but increased with increasing loads. A reasonable explanation for this is yet lacking.

The oxygen uptakes ($ml \cdot min^{-1}$) found in this study during walking and standing with the different loads were well predicted (r=0.97) with an equation formulated earlier (Holewijn et al. 1992)(Figure 9).

$$Vo_2 = 4.1 \cdot \text{body mass} + 0.367 \cdot (\text{body+load mass}) \cdot v^2 + 2.017 \cdot \text{shoe mass} \cdot v^2 \quad (ml \cdot min^{-1})$$

with: *v: walking velocity* ($km \cdot h^{-1}$);
body, load, and shoe mass (kg)

This regression formula consists of three components. The first term represents the standing metabolic rate, the second term represents the oxygen uptake due to displacement of body mass and centrally placed trunk loads. The third term represents the additional, far higher oxygen uptake per kg shoe mass.

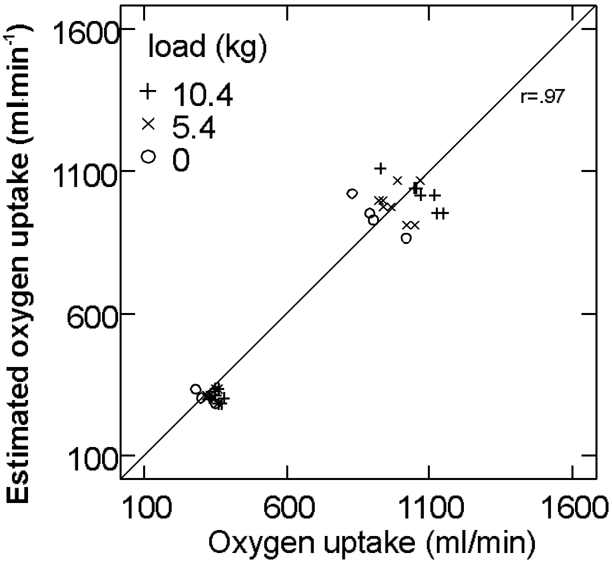


Figure 9. The relation between the measured oxygen uptake ($ml\cdot min^{-1}$) and the predicted oxygen uptake ($ml\cdot min^{-1}$) during standing and carrying a load of 0, 5.4 and 10.4 kg.

Several studies have shown that an oxygen uptake around 40% Vo_2 max and a heart rate around 110 $beats\cdot min^{-1}$, can be maintained for periods of less than 2 h (Evans et al. 1980, 1983; Grandjean 1967; Michael et al. 1961; Nag et al. 1980; Nag and Sen 1979; Rutenfranz 1985). The measured metabolic and cardiovascular strains in the present study were below these levels so it may be concluded that for a young male population loads up to 10.4 kg would not limit the endurance time of walking. However, for a different age-group or sex these tolerance limits may be exceeded (Jorgensen 1985). Combining the data of the effect of age and sex on Vo_2max (Astrand and Rodahl 1986) with the energy prediction formula of Pandolf et al. (1977) one can estimate the external mass at which the metabolic tolerance limit is reached (Table 1).

Table 1. The estimated backpack load (kg) for men and women, at which the metabolic limit is reached at a walking speed of 1.33 $m.s^{-1}$ for three age-groups. It should be noted that this load is the sum of the mass of the backpack, and the mass of the clothing/equipment and the footwear.

Age (years)	External mass (kg)	
	Man	Woman
20	32	19
40	17	4
60	5	—

-: For a woman aged 60 years the metabolic tolerance limit is already exceeded without an external weight

It should be noted that these predictions are based on body masses of 60 and 70 kg for an average woman and man and a surface consisting of a flat hard top road. Other conditions will result in different predicted external loads. In particular, different terrains will increase the metabolic strain (Pandolf et al. 1976).

Muscular strain

Since Rohmert (1966) published the endurance curves for static contractions of the arm muscles, it has long been assumed that contractions below 15% MVC could be maintained indefinitely. The results of recent studies have shown that static contractions should be around 5% MVC to avoid the effects of fatigue after 1 h (Björkstèn and Jonsson 1977; Hagberg 1981; Jonsson 1978; Sjøgaard et al. 1986). In this study standing with the two loads resulted in average force levels for the descending part of the trapezius muscle well below 1%MVC. No differences existed between the two types of carrying system, although using the Military backpack most of the load was supported on the shoulders, in contrast to Cust. A possible explanation may be that while standing with a backpack the shoulder girdle is, for the major part, resting on the ribcage, needing only small muscle forces to stabilize the shoulder girdle and, therefore, no differences between the two backpacks should be found. However, walking with a load significantly increases the force level generated by the descending part of trapezius muscle, without surpassing the 5%MVC limit. It can be concluded that the force level generated by the descending part of the trapezius muscle during the carrying condition was below the static force level that can be maintained for a long period.

The cyclic variations in force while walking (Figure 7) can be explained from the kinematics of walking. According to Stokes et al. (1989) the pelvis rotates in the frontal plane opposite to the shoulder girdle during most of the stride cycle. The shoulder on the opposite side to the leg striking the ground is lifted and rotated forward. When this movement of the shoulder is impeded due to a load supported by the shoulder, the trapezius muscle has to generate a higher force to overcome this. From the data on the force generated by the descending part of the trapezius muscle during load carrying using the military backpack, it can be seen that with a load of 5.4 and 10.4 kg the extra absolute force level (above walking with no load) was 8.4 and 17 N per shoulder, respectively. The extra force generated by the descending part of the trapezius muscle doubled with a doubling of the load carried in the Military backpack . The force level during load carrying using the Custom built backpack was not significantly influenced by the load level, showing that most of the load had been transferred to the hips by the flexible frame, leaving on the shoulder only a constant load needed for stabilisation.

Skin pressure

According to Husain (1953), a skin pressure of more than 14 kPa (105 mm Hg) results in irritation, redness and, for an exposure time of 2 h, in subcutaneous oedema and inflammation of the dermis and underlying tissue. Besides the amount of pressure, the duration of the pressure is also an important factor in the development of the symptoms (Kosiak 1958; Stobbe 1975). Recently Sangeorzan et al. (1989) reported that for skin over muscle, a pressure of less than 10 kPa (75 mm Hg) reduces the transcutaneous partial pressure of oxygen, used as an index for local circulation, to zero. Therefore, it is assumed that in order to avoid these effects, the pressure applied on the skin under the shoulder straps should be below 10 kPa (75 mm Hg). The Military backpack exceeded this limit on the top of the shoulder for both loads. The Custom built backpack caused skin pressures far below this limit. High pressures can probably cause arm muscle weakness due to temporary failure of the superficial nerves in the plexus brachialis as found by Funaski (1978) and Rothner et al. (1975). As the skin pressure was the only strain clearly exceeding the tolerance limit, it is concluded that the frequent complaints during walking using the Military backpack, with relatively light loads, were caused by pressure on the skin under the shoulder straps. From the pressure measurements it can be seen that in the custom built backpack, the frame transferred a considerable part of the mass to the hips. This is not just displacing the problem to the waist, since the contact area between the waist belt and the hips can be quite large, by that reducing the pressure. The disadvantage is that to prevent the waist belt slipping off the hips it must be pulled tight, by that increasing the pressure on the skin. Data of Scribano et al. (1970) have shown, however, that the hips are less sensitive to pressure by a factor of three, so it may be concluded that load bearing by the hips is preferable to load carrying on the shoulders.

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Correlates of Load Carriage Performance Among Women

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Summary

To examine correlates of the speed at which female soldiers carrying loads could cover ground on foot, 12 volunteers (mean±SD: 25.3±6 years, 166±7 cm, 61.3±7 kg) were timed over 3.2 km while carrying loads of 14, 27, and 41 kg. Respective course times were 25.7±3, 30.7±4 and 36.9±5 min, which differed significantly ($p<0.05$) from each other. A correlation analysis with independent variables of body mass, bitrochanteric diameter, hip circumference, shoulder diameter, height, age, relative $\dot{V}O_{2\ max}$ (ml/kg/min), absolute $\dot{V}O_{2\ max}$ (l/min), percent body fat, fat free mass, and self-reported scores on the Army fitness test (pushups, situps and 3.2 km run) revealed that absolute $\dot{V}O_{2\ max}$ and 3.2 km run time were the best predictors of loaded 3.2 km run time for each load. Correlation coefficients for the 14, 27 and 41 kg load course times respectively were -0.64, -0.61 and -0.70 for absolute $\dot{V}O_{2\ max}$ and 0.80, 0.67 and 0.75 for the 3.2 km run time. For the 14 and 27 kg loads there were no anthropometric measurements that correlated well with run time. However, with the 41 kg load, there were good relationships ($p<0.1$) between 3.2 km run time and body mass ($r=-0.59$), height ($r=-0.55$), hip circumference ($r=-0.52$) and fat free mass as determined from skin folds ($r=-0.56$). This suggests that larger subjects with greater muscle mass, for whom the 41 kg load represented a smaller percentage of their bodyweight, were able to carry the heaviest load faster than smaller, less muscular subjects.

Introduction

When motorized vehicles are unavailable, incapable of traversing the terrain, or easily detectable by the enemy an army must depend on soldiers to carry loads in the field. Success at accomplishing a mission and survival on the battlefield is dependent in part on the speed at which a unit of foot soldiers can cover ground while carrying a load. However, the unit's speed is limited by the speed of its slowest member. Thus, a screening tool that would allow selection of soldiers likely to be capable of the desired load carriage speed would contribute to the effectiveness of the fighting force. For safety and convenience, a screening battery based on easily measured anthropometric, aerobic endurance, and muscular endurance variables is preferable to actual load carriage tests.

In this study female soldiers served as the research subjects. It is important to study the ability of women to perform combat-related tasks because 1) during basic training, all female recruits currently participate in load carriage marches and other combat maneuvers, 2) women have been well integrated into combat-support military occupational specialties (jobs) and they could easily become involved in combat if front lines shift or the enemy infiltrates behind our lines (this happened during the Gulf War).

Studies in which physiological and anthropometric determinants of load carriage performance (LCP) have been examined were undertaken mainly by military groups. Maximal oxygen uptake ($\dot{V}O_{2\ max}$) was found to be one of the best predictors of LCP in several studies (7, 13, 22, 21). The role of fat free mass was found to have a large influence as well (13, 21, 16). No statistically significant correlations were found between % body fat and LCP in any of the studies reviewed, suggesting that an increase in % body fat does not adversely affect performance in a non-obese physically fit cohort. Unloaded 3.2 km run time was a fairly good predictor of LCP ($r=0.60$-0.63) in two separate studies by Kraemer et al. (15 and 14). In only three

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previous studies was the impact of load carriage on female subjects examined (14, 22, 21). LCP has been assessed in previous studies using a relatively narrow range of loads.

This paper is based on analysis of data from an experiment designed to compare the physiological, biomechanical, and maximal performance effects of two different backpack systems on female soldiers carrying three different loads (11). The purpose of the current paper is to describe how anthropometric and aerobic endurance measures related to backpack load carriage performance of females on a 3.2 km load carriage course. The study is unique in several aspects. Load carriage data from females is limited, especially at the 3.2 km distance, and in only one other study was LCP using 3 different loads examined. In the present study, the heaviest load used for the 3.2 km test was greater than in any previous study reported for women.

Methods

The volunteers for this study were 12 female soldiers who were medically screened and from whom written informed consent was obtained prior to their participation. Several had sedentary jobs, but most had jobs that were physically demanding, such as Military Police work.

Subjects were tested under three load conditions. The “fighting load” weighed 14.2±0.59 kg (31 lb) and consisted of the Battle Dress Uniform (BDU), boots, body armor, Kevlar® helmet, equipment belt, load-carriage vest, dummy grenades, ammunition clips, and M-16 rifle. The “approach load” included the fighting load plus 13.6 kg of weight in a backpack, totaling 27.2±1.2 kg (60 lb), while the “sustainment load” included the fighting load plus 27.2 kg of weight in a backpack, for a total of 40.6±1.1 kg (90 lb). The weight in a pack consisted of steel plates, sandbags, or containers filled with small metal objects, held in place in the pack with foam blocks. The backpacks used in testing were external-frame Army packs.

The location of the center of mass of a backpack had been shown in one of our previous experiments to affect energy cost by as much as 24% (19). The study showed that the best placement of the pack center of mass for efficient load carriage was as close as possible to the back and as high as possible in the pack. This guideline was used for the present study. The center of mass of the 14 kg load system was actually just in front of the subject (due to placement of the magazines and grenades on the front of the load carriage vest). For the 27 kg load, the center of mass was slightly in front of the frame of the backpack, and for the 41 kg load, it was slightly behind the frame and a bit higher than for the 27 kg load. These center of mass locations do not take into account the weapon carried in the hands in front of the body, which would bring the load center of mass even further forward.

The loads selected for the study are similar to those cited in the U.S. Army field manual on foot travel (4). It states that up to 72 lb may be carried on "prolonged dynamic operations" and that "circumstances could require soldiers to carry loads heavier than 72 lb, such as approach marches through terrain impassable to vehicles or where ground/air transportation resources are not available. These ... loads can be carried easily by well-conditioned soldiers. When the mission demands that soldiers be employed as porters, loads of up to 120 lb can be carried for several days over distances of 20 km a day" and "loads of up to 150 lb are feasible.” Soldiers in actual combat operations have often reported carrying loads well in excess of 100 lb (45 kg).

Dependent Variables

Because the speed at which a soldier can move when approaching and traversing the battlefield can greatly affect the outcome of a battle, one means of evaluating soldier performance is to time simulated versions of this type of movement. Thus the research volunteers were timed carrying various loads as they traveled 3.2 km by foot as fast as they could.

Subjects traversed at maximal speed a 3.2 km paved course that included four small hills. Each soldier was instructed to give her best effort in completing the 3.2 km distance in the fastest possible time. The volunteers performed this test six different times, carrying each of the three different loads twice, with at least 2 days of rest between adjacent trials. Each subject was accompanied by a test technician who was responsible for helping the volunteer in the event of injury, making any pack adjustments that became necessary en route, ensuring the test route was accurately followed, and providing encouragement.

Soldiers performed 2 trials with each of the 3 loads (14, 27, and 41 kg) on the 3.2 km course. The volunteers carried the different loads in a balanced order so that no load was more likely than another to be tested in any particular part of the testing order. Each pair of same-load trials, which did not differ significantly from each other, was averaged before statistical analysis was performed. Correlation analyses and stepwise multiple regressions were performed to determine if anthropometric and aerobic endurance variables related to 3.2 km run time with the 3 different loads.

Independent Variables

Maximal oxygen uptake. Oxygen uptake was measured using a continuous, grade-incremental, treadmill protocol and a computerized expired-gas collection, analysis system custom-developed at USARIEM. To ensure the safety of the volunteer, the output of a single lead (V_5) electrocardiograph was monitored during the entire test by trained personnel. Volunteers were connected to the gas collection apparatus via a mouthpiece, large 2-way Hans Rudolph valve, and flexible tubing supported by an overhead support-arm. The gas analysis system incorporated a KL Engineering air-flow turbine, an S-3A oxygen analyzer, an LB-2 carbon-dioxide analyzer, a Yellow-Springs thermister, a Hewlet-Packard electronic square wave counter, and a Hewlett-Packard desktop computer and printer which determined and printed, at pre-selected intervals, the rate of oxygen consumption and ventilation per minute expressed both in absolute terms (L/min) and relative to the individual’s body mass (ml/kg/min). The volunteer first warmed up by running for 5 minutes at 5 miles per hour with the treadmill bed horizontal. After a 5 minute rest, the volunteer remounted the treadmill and started running at a speed determined to be moderate based on her heart rate response during the warm-up run. The treadmill grade was set at a 5 percent incline at this time. At 3 minute intervals, the treadmill grade was increased by 2 percent without changing the treadmill speed. A volunteer was considered to be at maximal oxygen uptake if, 3 minutes after a grade increase, she had not increased oxygen uptake by at least 2.0 ml/kg/min. The volunteers generally reached maximum oxygen uptake on the treadmill within 10-12 minutes after starting the test. The mouthpiece was inserted for the last 90 seconds of each 3-minute interval and oxygen uptake was calculated and printed every 30 seconds.

Physical fitness. All soldiers are required to take the Army Physical Fitness Test (APFT) twice a year. The self-reported results of the volunteers’ most recent physical fitness tests were analyzed to determine if they were useful predictors of load carriage performance. The three components of the test are the maximum number of sit-ups that can be done in 2 minutes, the maximum number of push-ups that can be done in 2 minutes, and time taken to run 3.2 km. Using worksheets published by the Department of the Army (5) absolute scores on the three subtests are assigned points based on the soldier’s age and sex, and points for the three subtests are added to get the total APFT score. An advantage of using APFT test data is that soldiers train for the test and try to do well because a good score increases their chances of promotion. Although one might question the accuracy of self-reported data, we felt that the self-reported values were reasonably accurate because the self-reported 3.2 km run time correlated well with times for the loaded 3.2 km run. It is unlikely that soldiers would forget their most recent APFT scores, since it is of such importance in the military environment.

Anthropometric measures. The following variables were also evaluated as predictors of load carriage performance: age, height, bodyweight, biacromial and bitrochanteric diameters, hip circumference, percent body fat determined from equations by Durnin and Womersley (6) using skinfolds, and lean body mass.

Results

Volunteer Characteristics

Table 1 presents the descriptive characteristics of the 12 women who participated in this study.

Table 1. Descriptive Characteristics of Subjects

Variable	Mean ± SD	Range
Age (yr)	25.3±5.5	19.4-38.2
Height (cm)	166.0±6.5	154.7-174.8
Body mass (kg)	61.3±6.7	52.5-72.0
Body fat (%)	25.7±3.22	20.6-31.5
Fat free mass (kg)	45.5±3.7	41.3-50.9
Shoulder diameter (cm)	37.0±1.4	35.2-40.2
Hip diameter (cm)	32.2±2.1	29.6-36.7
$\dot{V}O_{2\,max}$ (ml/kg/min)	48.8±4.6	41.9-54.4
$\dot{V}O_{2\,max}$ (L/min)	3.0±0.5	2.4-3.7
3.2 km run time (min)	17.0±1.1	14.7-18.3
Push-ups (#)	41±12	26-64
Sit-ups (#)	68±10	54-85
APFT score (pts)	256±24	216-290

Table 2 shows that as load increased, time to complete the 3.2 km course also increased. Soldiers took 19% more time to cover the distance with the 27 kg load than with the 14 kg load, and 44% more time to cover the distance with the 41 kg load than with the 14 kg load. There was a strong tendency for volunteers who did well with one load to do well with the other loads. Course times with the 14 and 27 kg loads produced a coefficient of correlation of 0.65. Course times with the 14 and 41 kg loads produced a coefficient of correlation of 0.50, while course times with the 27 and 41 kg loads produced a coefficient of correlation of 0.80. Thus, as expected, course times with more similar loads were more closely related.

Table 2. 3.2 km Load Carriage Course Times (min)

Load	mean (SD)	Range
14 kg	25.7±2.6	20.0 – 29.6
27 kg	30.7±3.7	24.5 – 38.3
41 kg	36.9± 4.8	28.6 – 44.6

Course times with the different loads differed significantly ($p<0.05$)

Correlation coefficients of various independent measures with 3.2 km load carriage course time are seen in Table 3. Absolute $\dot{V}O_{2\,max}$ and 3.2 km run time were the best predictors of course time. The coefficients of correlation between $\dot{V}O_{2\,max}$ (L/min) and 3.2 km time for soldiers carrying the 14, 27, and 41 kg loads, respectively, were -0.64, -0.61 and -0.70. The negative correlations indicate that subjects with higher absolute $\dot{V}O_{2\,max}$ took less time to cover the course. The coefficients of correlation between APFT 3.2 km run time and 3.2 km load carriage time were 0.80, 0.67, and 0.75 for soldiers carrying the 14, 27, and 41 kg loads respectively. All these correlations were statistically significant ($p<0.05$).

Table 3. Correlation Coefficients of Various Independent Measures with 3.2 km Load Carriage Time

Dependant variable	14 kg load	27 kg load	41 kg load
Body mass (kg)	-0.45	-0.42	-0.59*
Height (cm)	-0.29	$-0.50^{\#}$	$-0.55^{\#}$
Hip circumference (cm)	-0.42	-0.36	$-0.52^{\#}$
Fat mass (kg)	-0.41	-0.29	$-0.53^{\#}$
Fat free mass (kg)	-0.41	-0.47	$-0.56^{\#}$
$\dot{V}O_{2\,max}$ (ml/kg/min)	$-0.56^{\#}$	$-0.53^{\#}$	$-0.51^{\#}$
$\dot{V}O_{2\,max}$ (L/min)	-0.64*	-0.61*	-0.70*
3.2 km run time	0.80*	0.67*	0.75*
Push-ups (#)	-0.24	-0.29	-0.09
Sit-ups (#)	-0.28	-0.18	0.49
APFT score (pts)	0.02	0.33	0.19

*p<0.05
$^{\#}$p<0.1

For the 14 kg load, no anthropometric measurements correlated well with run time. With the 27 kg load, height showed a -0.50 correlation with course time, meaning that taller volunteers tended to be faster. However, with the 41 kg load, greater body size was associated with faster course time (body mass: r=-0.59, p<0.05; height: r=-0.55, p<0.06; hip circumference: r=-0.52, p<0.08; and skinfold determined fat free mass: r=-0.56, p<0.06). This suggests that the larger subjects with greater muscle mass were able to carry the heaviest load faster. It appears that the heavy pack slows the speed of larger, more muscular subjects to a lesser degree than it does for the smaller, lighter subjects, because the 41 kg load represents a smaller percentage of the larger person's bodyweight.

In the population tested, which had a body fat range of 21%-32%, having a higher percent body fat was not detrimental to performance. The three fastest subjects with the 41 kg load averaged 27.5% body fat, while the three slowest subjects averaged 23.0% body fat. The faster soldiers also had a greater fat free mass (47 kg) than that of the slower soldiers (42 kg). Apparently the greater fat free mass of the faster soldiers had a positive effect on their performance that outweighed any negative effect of their greater percent body fat.

In the stepwise multiple regression analysis for prediction of 3.2 km course time (Table 4), the APFT 3.2 km run time entered the regression model for each of the three loads. Absolute $\dot{V}O_{2\,max}$ entered the regression equation for both the 27 kg and 41 kg loads, while hip-width entered last into the equation for both the 14 and 27 kg loads. The number of push-ups the females could do in 2 minutes came into the equation to predict 41 kg load carriage course time.

Table 4. Regression Equations for 3.2 km Load Carriage Test

14 kg load carriage time, min = 1.8 (3.2 km run time, min) + 62.8 (shoulder width, m) – 45.4(hip width, m) -13.7
$R^2 = 0.82$

27 kg load carriage time, min = 1.7 (3.2 km run time, min) – 3.4 ($\dot{V}O_{2\,max}$, L/min) + 77.9 (hip width, m) -12.9
$R^2 = 0.73$

41 kg load carriage time, min = 2.2 (3.2 km run, min) + 0.12 (number of push-ups) – 3.4 ($\dot{V}O_{2\,max}$, L/min)+3.8
$R^2 = 0.69$

Discussion

This study has demonstrated that indices of aerobic fitness and body size are related to load carriage performance among women. This study is novel in that load carriage performance was evaluated using three different loads, with the 41 kg load being heavier than any load previously reported in the literature for women. The 41 kg load was deemed of particular relevance for the military, as it is typical of the load a solider must carry on a sustained march.

Maximal aerobic capacity related well to LCP at all three loads. Absolute $\dot{V}O_{2\ max}$ (L/min) was a better predictor of LCP than was relative $\dot{V}O_{2\ max}$ (ml/kg/min). This is not surprising because absolute $\dot{V}O_{2\ max}$ reflects both aerobic fitness and body size, while relative $\dot{V}O_{2\ max}$ reflects only the former. In addition, smaller people tend to have higher relative $\dot{V}O_{2\ max}$ because the ratio of arterial cross-sectional area to body volume decreases as body size increases (2). All else equal, larger, more muscular subjects, can carry loads more effectively than smaller, less muscular ones. Our data are in agreement with other studies also reporting that absolute $\dot{V}O_{2\ max}$ correlates more highly with LCP than does relative $\dot{V}O_{2\ max}$ (13, 21, 7).

As the measurement of maximal aerobic capacity requires laboratory equipment and personnel unavailable at most military installations, we also evaluated a surrogate and field expedient measure for aerobic fitness (i.e., self reported APFT 3.2 km run time). 3.2 km run time was more highly correlated than absolute $\dot{V}O_{2\ max}$ with LCP (Table 3). However, for the 27 kg and 41 kg loads, 3.2 km run time was only a slightly better predictor of load carriage run time than was absolute $\dot{V}O_{2\ max}$. As the load increased, the volunteers worked at a greater percentage of their maximal oxygen uptake (~50% of max with the 41 kg load [11]); thus the ability to predict LCP based on $\dot{V}O_{2\ max}$ is strongest with the heaviest load. The unloaded 3.2 km run test becomes less similar to the load carriage test as the load increases; thus the ability to predict LCP from 3.2 km run time is greatest with the lightest load. However the correlation coefficient for run time was greater with the 41 than the 27 kg load. Self-reported APFT 3.2 km run time was the best predictor of overall LCP for this group of women. Two studies by Kraemer et al. (15 and 14, the latter done on women) also demonstrated a relationship between 3.2 km run time and LCP (r=0.63 and r=0.60, respectively).

Body size, as represented by variables such as body mass, fat-free mass, fat mass, height and hip circumference, emerged as a consistent predictor of LCP with only the heaviest load. Body mass, height and hip circumference all positively correlated with fat free mass (r=0.93, r=0.68 and r=0.72, respectively). This indicates that the larger individuals had more muscle mass. Thus, it is likely that the larger women in this study were also stronger. Muscle tissue is estimated to make up 42% of fat free mass in the reference woman (3), and fat free mass is related to muscle cross sectional area which is proportional to muscle strength (23).

While we did not assess muscular strength in the current study, several other studies have shown a clear relationship between muscle strength and LCP. Isometric, isokinetic and isotonic strength of the torso and upper and lower limbs have been reported to correlate significantly with LCP (13, 7, 16, 22, 21). Additional support for the connection between muscle strength and LCP comes from studies demonstrating that strength improvements after several weeks of resistance training are associated with LCP improvements (15). Improvements in upper body strength with training have been suggested to be essential to improving the LCP of women (18). This finding may explain why push-ups came into the regression model for 41 kg load carriage course time; those individuals with greater upper body strength were better able to resist the tendency of the shoulder straps to pull the shoulders back causing discomfort and a biomechanically unfavorable walking position.

The role of fat free mass in LCP is seen more dramatically when its effect is removed via partial correlation. The correlations between run times with the 41 kg load and other anthropometric variables related to body size fell from good to insignificant when the effect of fat free mass was removed. The association between LCP and fat free mass has also been reported to be significant in other load carriage studies (13, 21, 16). In addition, correlations between absolute $\dot{V}O_{2\ max}$ and both 27 kg and 41 kg load carriage times were reduced when the effect of fat free mass was eliminated. For the 27 kg load, the coefficient for absolute $\dot{V}O_{2\ max}$ dropped to -0.46 from -0.61, and for the 41 kg load dropped to -0.52 from -0.70. Absolute $\dot{V}O_{2\ max}$ and fat free mass correlated highly in this experiment (r=0.87), as it has in other studies (13, 7). Because a greater amount of active muscle tissue requires a greater amount of oxygen during exercise, absolute $\dot{V}O_{2\,max}$ relates to fat free mass. Therefore the correlation between LCP and $\dot{V}O_{2\,max}$ is partially influenced by fat free mass.

In this study, in which none of the volunteers were overweight, body fat was not found to be detrimental to LCP. In fact, increased fat mass was actually associated with shorter 3.2 km run times with the 41 kg load (r=-0.53, p<0.08). In addition, fat free mass and fat mass were positively correlated (r=.70); the volunteers who had greater fat mass also had greater fat free mass, presumably including muscle tissue. It is probably for this reason that subjects with greater fat mass were able to carry the extra fat without a decrease in performance compared to smaller, leaner subjects. Rayson et al. (21) also found in a group of men and women that greater levels of body fat were associated with better LCP with a 15 kg load. These findings can be explained by the positive correlation between adiposity and muscularity. (24, 17). However, because fat provides no benefit in itself to lifting or carrying heavy loads, it is likely that the subjects who did well carrying the backpack loads would do even better if they lost body fat, assuming that they could maintain their fat free mass.

It has been suggested that it takes a different body type to carry loads well than to be a good runner (10). As described above, larger more muscular individuals are more successful at carrying heavy loads, whereas the typical build of competitive middle to long-distance runners is lean and slight (20). The current study, however, showed good correlation between a 3.2 km unloaded run time and a 3.2 km load carriage time; individuals who carried heavy loads well also did well running unloaded. The volunteers had a relatively high overall fitness level. They were more aerobically fit than the average female according to normative data (1). $\dot{V}O_{2\,max}$ (ml/kg/min) ranged from 41.9 to 54.4, which represents the 80-99th percentile for females age 20 to 29.

In summary, the analysis described in this paper was an attempt to identify anthropometric and physical fitness variables that correlated with load carriage performance over a 3.2 km course. Absolute maximal oxygen uptake correlated well with 3.2 km load carriage time, across each of the three loads tested. The APFT, which is based on maximal number of sit-ups and push-ups performed and 3.2 km run time, made apparent its value for prediction of military physical performance. The 3.2 km unloaded run time APFT component was the best correlate of 3.2 km load carriage time for all three loads. Individuals of larger size and muscle mass are capable of carrying heavy loads (41 kg) faster than their smaller less muscular counterparts. Within the body composition range of our subjects, body fat does not appear to be a detriment to load carriage performance.

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A Combination of Biomechanical and Physiological Approaches for Determination of Optimal Load Distribution

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Summary

France is developing an integrated soldier ensemble that will improve soldier protection, survivability and sustainability. Improvement of the soldier's load carrying capacity remains an important step that will contribute to the maintenance of good health and protection against the side effects induced by soldier systems. A number of factors can influence the energy cost associated with locomotion. The aim of many studies has been to determine the level of oxygen uptake that can be maintained without physical fatigue. A myriad of kinematic and kinetic parameters may directly or indirectly influence the energy cost of locomotion, especially when subjects are walking with loaded backpacks. While the metabolic energy cost of human movement is easy to estimate by the global measure of total body oxygen consumption (V_{O2}), a variety of computational techniques have been suggested as appropriate for the calculation of mechanical power. The changes in energy of the centre of mass (via ground reaction forces) have been frequently used to estimate the mechanical power of locomotion. One limitation of these measures is that they do not include the work done in moving the limbs and arms. This work, often termed “internal work”, is one essential component of total mechanical work associated with locomotion. Because measures of mechanical power which do not include contributions from all of the internal and external work done may provide misleading information, recent methods involving a segmental analysis have been suggested to determine the changes in the energy of individual body segments. Thus, measures of both oxygen consumption during walking and load carriage, and mechanical work are two essential steps in the assessment of the relationship of physiological energy expenditure to mechanical factors. Our approach to the study of human movement efficiency involves determination of the mechanical efficiency of human locomotion with backpack loads simultaneously with measurement of biochemical, cardiovascular, muscular and mechanical responses that occur during treadmill walking. In the framework of the development of the French soldier system, the first step of our program is to determine the optimal distribution and placement of the load by examining the changes in mechanical work, muscular activity and energy cost of walking on a treadmill.

Introduction

Despite considerable modernization of military equipment, load carriage by backpack is still a requirement for soldier on the battlefield. The tolerance of load carriage is critical for soldier performance and prevention of side effects such as localized muscular discomfort and muscular injury leading to fatigue. Particular attention should be paid also to the maintenance of efficiency of locomotion during prolonged walking in order to prevent progressive shifts in the metabolic energy cost and in core temperature.

Efficiency of human movement

Efficiency of human movement is an important topic in exercise physiology. As for athletes, the efficiency of movement is a critical factor for the maintenance of a given task for soldiers. A number of factors can be identified which would be likely to have an influence on the efficiency of movement, among them biochemical, physiological, biomechanical and psychological factors. When one attempts to estimate the efficiency of human movement, the most common definition used is that set forth by Stainsby et al. (1980):

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$$\frac{\text{mechanical work}}{\text{energy expended}}$$

While equations exist to predict the energy expended and the metabolic energy cost of locomotion, there is a great intersubject variation in the oxygen uptake at a given walking speed, under specific terrain conditions and with external loads. It is not possible to accurately attribute these individual variations in the energy cost of locomotion to particular factors known to contribute to the efficiency of human movement (Cavanagh and Kram, 1985). Although individuals vary considerably in the amount of energy expended to perform the same submaximal task, these differences in oxygen consumption (VO_2) cannot directly be interpreted as differences in efficiency. At a given walking speed, a high value of VO_2 may reflect a high mechanical work with similar values of muscular efficiency. Because it is not practical to measure true effectiveness in human subjects, it is thus clear that an integrated approach of the biomechanical and physiological characteristics of human locomotion appears very useful. This is the case for prolonged walking with external loads.

Physiological strain of walking with external loads

Because VO_2 for a given task has been emerged as a practical index for the evaluation of performance during endurance activity, an extensive amount of research has been conducted to study the energy expenditure during walking while carrying external loads. The general conclusions of these studies have been that the energy cost of walking is affected by the velocity, terrain factors such as grade and surface, the weight, size and shape of the load carried. Subsequently, mathematical prediction models of the energy cost of walking or running with graded loads have been developed, principally by the Natick's laboratory (Pandolf et al., 1977; Pimental and Pandolf, 1979).

One point deserves particular attention. In military operations soldiers are required to cover long distances and the majority of studies dealing with determination of the energy cost of walking with external loads considered tasks of relatively short duration. One important question concerns the effects of load carriage on the economy and/or muscular efficiency of prolonged walking over several hours.

Many previous studies demonstrated a gradual increase in VO_2 during prolonged activities such as walking, running or bicycle exercise. Epstein et al. (1988) showed for the first time an increase in the energy cost of walking over time while carrying external loads. Results of this study showed that carrying 25 kg (37 % of body weight) did not significantly affect the oxygen uptake expressed per kg body weight and external load while subjects walk at a constant speed of 1.25 m/s. However, carrying a heavy load, the energy cost per kg increased significantly over time in a linear fashion (Figure 1).

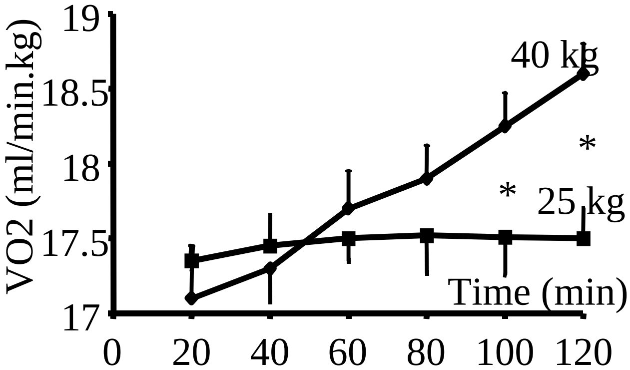

Figure 1. Effects of load carriage on oxygen uptake, expressed per kilogram of body weight+external load. (Epstein et al., 1988)

In accordance with these results, a progressive rise in VO_2 has been observed during a 12 km walk with heavy load carriage (Patton et al., 1991). In this study, it was interesting to note that VO_2 was found to increase over time for exercises as low as 27% of VO_2max. Several mechanisms may be responsible for the rise in the metabolic energy cost of walking, but it is very likely that altered biomechanics plays a key role in the decrease in walking economy. To our knowledge, this aspect has not been extensively studied and it would be interesting to examine the relationship between mechanical and physiological energy estimates during prolonged walking with external load.

For this purpose, we need estimates of metabolic energy cost and mechanical work of locomotion. The measure of oxygen consumption is generally accepted as a convenient method of assessing the metabolic energy cost of prolonged activity. However, the main problem is to have an accurate measure of the mechanical work done by the muscles in walking or running.

Mechanical work estimates during walking with external loads

The total mechanical work has been partitioned into the internal work due to the speed changes of body segments with respect to the body center of mass and the external work related to the position and speed changes of the center of mass in the environment:

Internal work

$$Eb(t) = \Sigma\ poE(i,t) + \Sigma\ trKinE(i,t) + \Sigma\ rotKinE(i,t)$$

$$Wi = \Sigma\ \Delta Ei$$

External work

$$We = Wpo + Wkin$$

$$= mg(Hmax-Hmin) + 0.5m(V^2max-V^2min)$$

where Wi is the internal work, poE(i,t) is the potential energy of the *i*th body segment at time *t*, trKin is the translationial kinetic energy of the *i*th body segment at time *t*, rotKin is the rotational kinetic energy of the *i*th body segment at time *t*; We is the external work, Wpo is the positive work against gravity, and Wkin is the positive work necessary to accelerate forward the center of mass during each step.

External mechanical work is frequently calculated from the total energy changes of the center of mass of the body, while internal work results from the summation of potential, translational kinetic and rotational kinetic energy components of all body segments. A number of authors have used a point mass model of the body to calculate the external mechanical work. The external work can be obtained from ground reaction forces. The total body energy as calculated from the center of mass energy is lower than the sum of segments energies, with average error varying between 16.2 to 40% (Winter, 1979). This apparent discrepancy is partly due to energy changes in reciprocal movements.

Force platforms are frequently used to measure ground reaction forces in order to calculate external mechanical work. Using this method, it has been previously shown that the mechanical work increased with increasing external load (Figure 2) (Pierrynowski et al., 1981). This finding was clearly expected but an interesting result was that mechanical work raised more slowly than metabolic cost.

One limitation of such a study is that all measurements have been done after only twelve minutes of walking. More marked alterations of mechanical work are expected after long term load carriage. An additional problem using force platform during walking, is the short measurement distance making it difficult to obtain constant velocity. Moreover, only few data are collected and the variability and asymmetry of dynamic step parameters can not be fully taken into account.

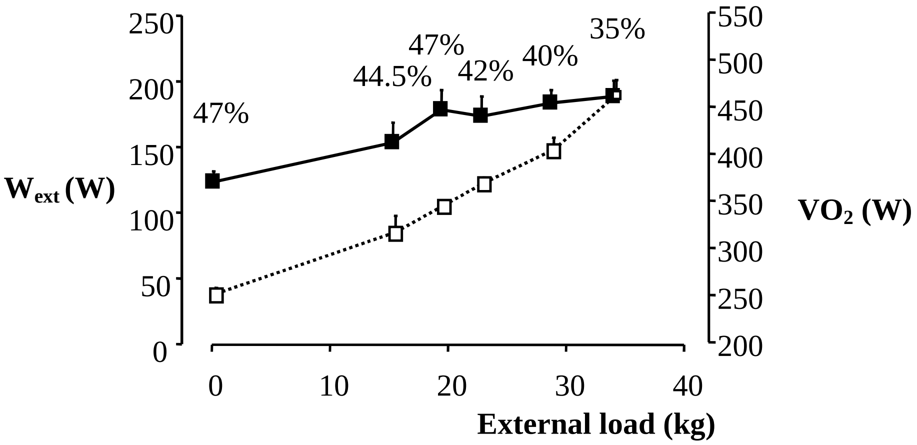

Figure 2. Changes in mechanical —■—, and metabolic ···□··· work rates with increasing external load et al., Pierrynowski et al., 1981)

On the other hand, one major limitation of such a approach evaluating mechanical work from the energy changes of the center of mass is that internal work can not be measured by means of force plate data. The main source of internal work is the kinetic energy changes of the limbs calculated from their velocity relative to the center of gravity. In theory, internal work can be estimated by motion analysis, but there are two major limitations of this approach. First, segmental energy increase may result from muscular contraction, transfer of energy between segments and/or elastic storage and return of energy, but there are great interindividual differences in the ability to store elastic energy under locomotor conditions. Energy can be stored in elastic tissues of the musculoskeletal system and subsequently contribute to the positive work. If elastic contributions are thought to be minimal in normal walking, it is likely that walking with external loads represents a favorable situation for elastic storage and return.

Secondly, many previous works demonstrated that the amount of energy expended differs for concentric and eccentric contractions (Williams, 1985). Thus, it would be incorrect to simply add the absolute values of the negative and positive changes in mechanical energy. Suggestions have been made to add to positive work only a portion of the calculated negative work, as exemplified by the following equation:

$$\mathrm{Mech(tot)} = \mathrm{Mech(+)} + [\mathrm{Mech(-)}/d]$$

Where Mech(tot), Mech(+), Mech(-) are the total, positive and negative mechanical works, respectively, and d is the efficiency of negative to positive muscular power. However, the d value could range from 2 to 6 (Williams, 1979). In conclusion, there is no valid measurements of total mechanical work of muscles during walking.

Although valid measurements of total mechanical work, including both external and internal work cannot be achieved, the effects of carrying loads on selected kinematic and kinetic parameters of walking gait is of great interest. Previous studies showed that the energy cost of running was associated with specific running pattern (Williams and Cavanagh, 1983). More interesting, we have previously shown that the energy cost of running increases over time. This increase in the energy cost observed at the end of a marathon or a triathlon is associated with an alteration of selected kinematic parameters (Hausswirth et al., 1997). These findings demonstrate that selected temporal and kinematic parameters could provide interesting information on the effects of load carriage on walking gait over time.

A pioneer study showed that the magnitude of the carried load only slightly affected the stride length in men (Martin and Nelson, 1986). Swing time and double-support time also showed little changes as the load was increased. Taken together, these results showed that the changes in global gait characteristics with load carriage were only small. However, one major problem with this study is that measurements were done after only short periods of walking. Moreover, when walking speed was not freely chosen but maintained constant, double and single support periods lengthened significantly as the load increased (Kinoshita, 1985).

The results of this latter study suggested that light external loads as light as 20% of body weight are liable to alter the pattern of gait of subjects not acclimatized to carrying activities.

Kinematic analysis of body segments and joint angles revealed that load carriage was associated with a greater knee flexion during the loading phase (Kinoshita, 1985). This finding has been explained as an adjustment of knee joint in order to function as a shock absorber to reduce the impact force. All these data suggest that gait characteristics are only slightly affected by load carriage. However, once again, motion analysis has been performed after short period of walking. But whether prolonged walking with heavy loads affects the energy cost of locomotion and alters the walking gait remains to be clearly determined.

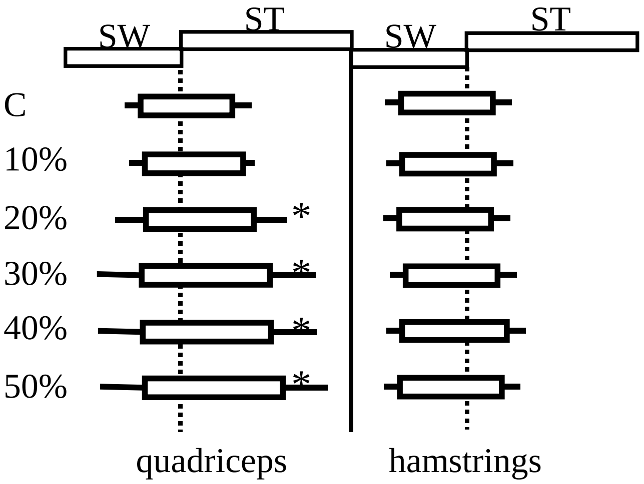

Figure 3. Activity patterns of two lower limb muscles in control walking (C) and when carrying external loads. SW, swing phase of the step cycle; ST, stance phase of the step cycle. *, significantly different from C. (from Ghori and Luckwill, 1985)

External load distribution

Many previous studies showed that heavy loads should be kept as close as possible to the trunk and center of gravity of the body in order to minimize fatigue and local muscle discomfort. Less known is the physiological cost of various modes of carrying a load close to the trunk. A previous study failed to show any significant difference between five modes of load carriage for several physiological parameters after one hour of walking (Figure 4) (Legg and Mahanty, 1985). However, carrying the load using a trunk jacket or half of the load in a standard backpack and the other half in a front pack was subjectively rated as more comfortable. Taken together, these results suggested that it is difficult to assess the optimum mode of load carriage only by physiological measurements such as oxygen consumption or heart rate.

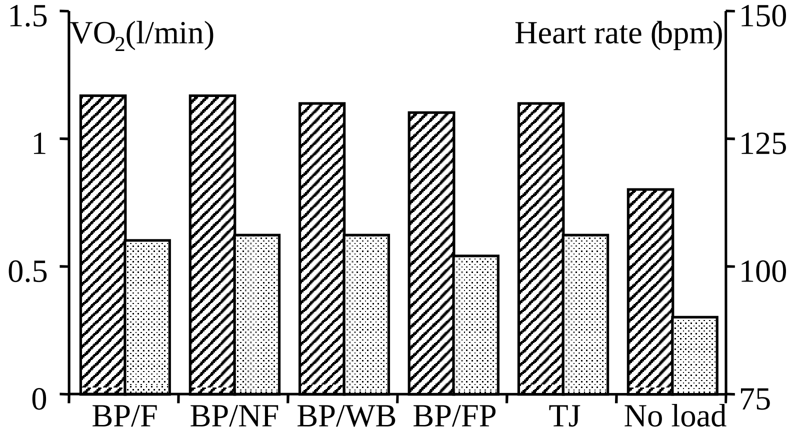

Figure 4 : Effects of five modes of carrying a load close to the trunk on oxygen uptake (VO_2) ▨ and heart rate ░ .
BP/F, backpack with frame; BP/NF, backpack with no frame
BP/WB, backpack with waist belt; BP/FP, backpack with frontpack; TJ, trunk jacket.
(Legg and Mahanty, 1985)

The acute effects of both light and heavy loads by means of two different carrying systems on some kinematic parameters of walking gait have been evaluated (Kinoshita, 1985). Step with and total support values while carrying loads using a double-pack system were more similar to those of normal walking with no load than for the backpack condition. The backpack system caused much greater forward inclination of the trunk and thigh than with the doublepack system. It was concluded that the doublepack system prevented the marked forward lean of the trunk expected while carrying heavy loads. The results of this study showed that the doublepack system was biomechanically more effective for carrying loads and that normal gait patterns were less affected when subjects used this carrying device than when they used a conventional backpack system.

Conclusion

In conclusion, the purpose of this paper was to discuss the methods used to evaluate the tolerance of load carriage systems. Load carriage systems are critical to soldier performance on the field and health, and thus an improved methodology is need in order to determine the suitability of a mode of load carriage. The experimental approach should determine the responses of several components to a backpack design, such as physiological (i.e. oxygen consumption and muscle activity measurements), biomechanical parameters (i.e. measures of ground reaction forces and selected kinematic characteristics of walking) and subjective measurements of discomfort. These measures should be compared to selective task performances as essential in military operations.

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The Effect of Load Position on Biomechanical and Physiological Measures during a Short Duration March

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Summary

This project attempted to determine the physiological and biomechanical effects of varying the centre of gravity of a load in a backpack in a short duration activity. Experienced soldiers (n=22) carried a 36.0 kg modified US Army ALICE backpack on a treadmill at 5.6 km/h for 15 minutes at 0° elevation. The subjects carried the load in three locations in a backpack (a high, middle and low distribution) and employed a load carriage vest as an 'alternative' distribution. This 'alternative' distribution balanced the load on the front and back of the subject. Oxygen consumption results showed no statistically significant difference between load locations ($P = 0.621$). Biomechanical analysis of the trunk lean and minimum included hip angles indicated significant differences between all 'alternative' comparisons as well as between the low and high load locations ($P < 0.05$). Maximum knee flexion angles were also shown to be significantly different between the low and alternate conditions. Cadence, stride length and displacement of the body COG did not show significant differences between conditions. Subjective evaluation indicated a strong preference for the alternative load condition due to the overall increased mobility and decreased feeling of discomfort. Under the conditions tested in this study it was concluded that load location does not significantly affect oxygen consumption but had a large impact on the perception of each load trial. A longer duration activity that imposes a larger strain on the subjects would be required to confirm this oxygen cost finding. The effect that trunk lean and the flexion angles will have on fatigue and energy consumption in a long-term exercise scenario has not been determined but should be undertaken in future studies. The subjective impact on the subjects should be considered as highly important and should therefore have an impact on the future design of load carriage systems.

Introduction

In order to make military personnel more effective they must reach their destination in the least possible fatigued state. Unfortunately, standard military loads are often 30 - 50 kg of rations, ammunitions and personal weapon. An objective set out by the Canadian Department of National Defence during the creation of the Integrated Protective Clothing and Equipment (IPCE) program was that analyses should focus on minimizing strain and pressures on the soldier while maintaining posture and freedom of gait (9).

Many studies have suggested that the logical choice for the load location would be closest to the body and to the body's centre of gravity (COG) as possible. This placement would reduce the excess moments about the body's COG and thus reduce the energy required to carry the load (1, 7). Other studies have shown that the use of a double pack, which carries half of the load on the front of the body and half of the load on the back, elicits a lower physiological cost (2, 7). Some studies of double packs as well as load carriage vests have shown that the Rating of Perceived Exertion (RPE) and heat stress increased when using these carrying methods, due to lack of ventilation. Another handicap associated with double packs and load carriage vests was the increase in task performance time when compared to the standard backpack due to encumbered movements (5, 7) and changes in gait pattern (6). Most physiologically based studies related to load

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placement or pack design were not sufficiently sensitive to pack COG locations. However, subjective responses to perceived comfort often provided additional insight into optimal load location when loads are carried on the back.

Many studies exist that examine either the biomechanics or the physiological effects of load carriage (3, 4, 8). While it is easier to examine either factor in exclusivity, those types of studies ignore the fact that the variables interact and are not mutually exclusive. Additionally, when only one modality is tested, it restricts the comparability of the study to others. One is unable to discern whether the biomechanical studies are eliciting the same physiological results that the physiological studies are, and vice versa. Only when studies use both modalities and a complete analysis of both factors, can one have a clearer, overall picture of the effects of load carriage on the carrier.

Materials and Methods

Twenty-two male subjects were recruited from the 1st Canadian Division Headquarters Signals Regiment from CFB Kingston. Each subject participated in four load trials in which 36 kg was carried in different locations. Three trials used a modified ALICE pack made by the US Army Natick Research Lab, which allowed for the alteration of the COG to high, middle and low locations spread by 13.3 cm each (Figure 1). The fourth trial used an alternative weight distribution system composed of a Velcro™ covered load carriage vest, upon which 18.0 kg was carried on the front, and 18.0 kg on the back. Each trial was 15 minutes in duration and consisted of a level treadmill walk at 5.6 km/h.

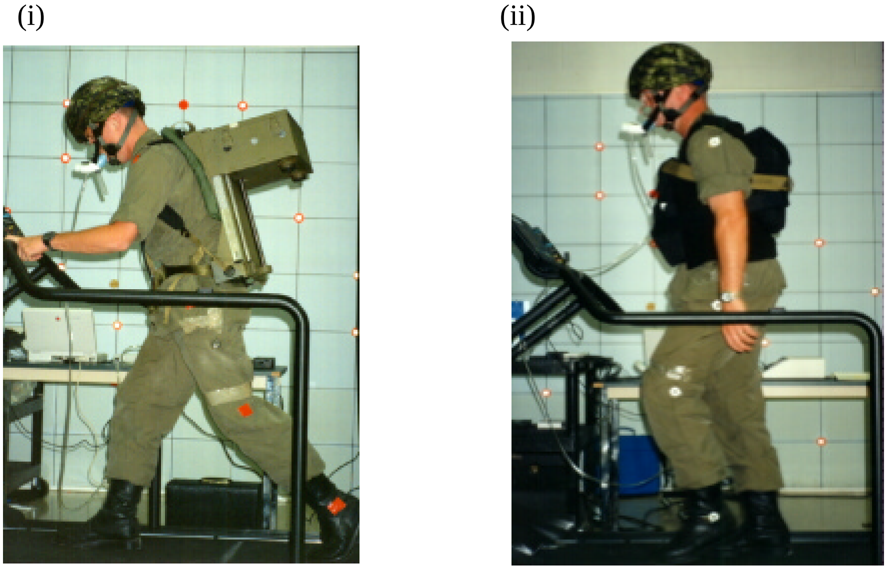

Figure 1. Load carriage systems used for human trials
(i) Backpack by US Army Natick Research Lab;
(ii) Load carriage vest by Pacific Safety Products Inc.

Oxygen consumption was measured using a portable metabolic cart (TEEM 100). For analysis, the last five minutes of steady state oxygen consumption was averaged and analyzed. For the kinematic analysis, joint markers were placed on the subjects at the 5th metatarsal, calcaneous, lateral maleolus, knee, greater trochanter and the shoulder. Using this set-up, we examined the joint angles at the knee and hip, their cadence, stride length, and the motion of the centre of mass of the subject during the gait cycle. It was hypothesized that there would be a significant difference between the alternate and other distributions since it was thought that the alternate would lead to a more normal gait pattern.

The subjects also completed subjective evaluations of the load location after each loaded trial. The questionnaire asked about overall acceptability, balance, thermal comfort, load control, and physical comfort (Table 1). It was hypothesised that subjects would rate the alternative load carriage system most acceptable due to its balanced load distribution. Conversely, the low load location was hypothesised to be ranked lowest due to the necessity for subjects to bend farther forward in order to bring the COG of the pack over the body's COG. A follow-up questionnaire was also administered to gather ratings of the load locations from worst (1) to best (4) for the four conditions.

Table 1. Questions asked on the post-test questionnaire – subjects answered these questions based on a 6 point rating scale from 1 (totally unacceptable) to 6 (totally acceptable)

	Question
1	Rate the overall acceptability of load position for marching
2	Rate your marching balance
3	Rate your load control ability
4	Rate your ease of mobility in marching order
5	Rate your level of physical comfort when marching
6	Was the load in a good position?
7	Would you be comfortable marching with your load in this position?
8	Rate your level of thermal comfort when marching

Results

The results of this study are summarized in Table 2. Oxygen consumption levels across load distributions were not significantly different. Results from the kinematic analysis indicated that significant differences existed between trunk lean angles, minimum included hip angles, and maximum knee angles. In all significant comparisons, the alternate position was one of the significantly different pairs. The maximum knee angle in the low position was significantly lower than the alternate position. The trunk lean and minimum hip angle were also significantly different with the same pattern of post hoc differences – the alternate condition was significantly lower than all other conditions in addition to the high condition being significantly lower than the low condition. Stride length, cadence and the displacement of the body's COG were not significantly different between load distributions.

Table 2. Measured variables and their significance levels including the conditions that exhibited the differences.

Measured Variable	p-Value	Post Hoc Differences
Oxygen Consumption	$P > 0.05$	None
Cadence	$p > 0.05$	None
Stride Length	$p > 0.05$	None
Displacement of Body COG	$p > 0.05$	None
Maximum Knee Angle	$p < 0.05$	Low < Alternate
Trunk Lean Angle	$p < 0.05$	Alternate < Low, Middle, High High < Low
Minimum Included Hip Angle	$p < 0.05$	Alternate < Low, Middle, High High < Low

Results from the initial questionnaire showed that the low pack position ranked least acceptable in 7 out of 8 categories that were examined. The alternate configuration ranked most acceptable in all categories except thermal comfort, where it was rated least acceptable (Figure 2). The follow-up questionnaire results showed that subjects disliked the low load configuration due to the extreme lean required, and this created undue stress on the back. The follow-up questionnaire also showed that the alternative load distribution was not ideal, as it constricted the chest, resulting in laboured breathing. The differences in overall preference were statistically significant ($p < 0.05$). Post hoc simultaneous statistical inference showed that significant differences existed between all paired configurations except high and alternative. Results also showed that 91% of subjects ranked the low load configuration as last or second to last choice with the most common reported problem identified as excessive body lean and undue stress on the lower back.

Discussion

There was no significant difference in the repeated measures ANOVA between load locations and oxygen consumption under the conditions that were tested in this experiment (Table 2). This result agreed with the study performed by Bobet and Norman (1), which reported that there was no discernible difference in energy cost (as extrapolated from heart rate) based on varying the location of the COG over a 90 m walkway at 5.6 km/h while carrying a 19.5 kg pack. These results, however, disagreed with the results of Datta and Ramanathan (2) who reported that the double pack (a pack which places some of the load on the front of the body) proved less costly in terms of energy. Datta and Ramanathan stated that this double pack was more energy conservative than six other forms of load carriage including the standard backpack carrying 30 kg at 5 km/h for 20 minutes. Their experimental design, however, used a seven level paired-t test for analysis without an apparent compensation for the loss of efficacy when multiple t-tests are performed. This may have given an artificial significance, especially when the difference between oxygen consumption at the load locations was very small.

Trunk lean and included hip angles were significantly different between all three backpack locations and the ‘alternate’ configuration and between the low and high permutations. For a subject to maintain balance with the total load over the body’s centre of gravity, trunk and total body leans are employed. Placing the load more vertically in line with the body’s centre of gravity reduces the moment about the hips caused by the backward pull of the backpack. The alternate configuration reduced the backward moment by dividing the load between the front and back of the subject. With this distribution, the line of action of the force caused by the load then passes close to the centre of gravity of the body, reducing the rotary moment that the load exerts. In a similar vane, a lower included hip angle would indicate a more upright gait. Bobet and Norman (2) clarified that in general, loads placed higher than the body’s centre of gravity cause a larger forward moment. Placement of the load below the COG causes a larger backward moment. Movement of the load over the body’s COG allows for the line of action of the load to fall in the same line as the body’s mass and, therefore, will reduce the muscle effort required to counter the load moments. This explains why the subject is in the most stable position for standing. However, this explanation falters when locomotion is considered, where the COG must be placed in front of the feet for forward motion. In this condition, a low COG is poorest since the subject must use trunk lean to move the COG in front of the feet. In terms of the knee angle, a higher knee angle is indicative of more normal gait. In this study, the low condition had knee angles that were significantly lower knee angles indicating a change from normal that is likely a form of compensation for the load and its distribution. Compared to baseline values, the subjects employed a shorter stride length and increased cadence while under load-carrying conditions. There were no differences between load conditions and stride length, cadence, or displacement of the COG.

The subjective responses from both the initial and follow-up questionnaires indicated that the lower the load placement, the poorer the subjects rank overall acceptability. Subjects reported that this lower load placement caused them to lean farther forward. This excess lean resulted in soreness of postural and neck muscles that are required to be constantly active in order to lean forward yet hyperextend the neck to see forward. There is a postural benefit to carrying the load higher. As discussed above, the higher the load was placed, the closer to baseline were the trunk lean and included hip angles. However, when the load was placed at the high end of the backpack, load stability decreased, which would make it unsuitable for uneven terrain. This may have increased muscular activity in the shoulder area during gait thus not reducing shoulder discomfort as much as expected. Both lean angles were significantly greater than the angles that were recorded when the load was balanced on the front and the back. The benefits of carrying the load balanced on the front and back are better manoeuverability and a reduction in back stresses. The downside of the alternative method was little or no skin-air circulation, leading to thermal discomfort. The follow-up questionnaire asked the subjects to rank the load locations from best to worst on a scale of one to four. Using these results, an overall ranking of the four load locations was possible. The responses indicated that the alternate configuration was the most preferred followed by the high middle and low placements in that order.

The relative importance of physiological, biomechanical or subjective variables is not known. For example, in selecting between high and alternative positions, a determination must be made about which factor is more important: manoeuvrability or thermal comfort. Future research should be directed toward development of a weighting factor for each family of tests to determine their relative importance to the subjects. For the military, this might involve tradeoffs related to “soldier effectiveness” while for recreational backpackers individual preferences might be the deciding factor. All else being equal, however, subjective evaluation should be viewed as very important in the overall effect of load location.

Under the conditions tested in this study there was no significant difference in oxygen consumption based on load location. However, since this non-significant result is contested in the literature, a longer activity duration that would impose a larger strain on the subjects might accentuate differences to a greater extent. Trunk lean, included hip and knee angles vary significantly with load location. A lower load placement increases trunk angle and decreases included hip and maximum knee angle. These statistically significant differences indicate that having the load distributed across the front and back of the body will lead to a more normal and upright gait. The effect that these lean angles will have on fatigue and energy consumption in a long-term exercise scenario has not been determined but should be undertaken in future studies.

This study has attempted to provide an integrated look at the effects of load location in a backpack. It is apparent that one cannot look at only one factor in the evaluation of a backpack or loading strategy. Subjective responses, for instance, may be able to distinguish differences between strategies that modern instrumentation may not be able to quantify. This does not suggest that backpack design rely solely on subjective information, but that it is used in combination with other empirical measures.

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Load-Speed Interaction Effects on the Biomechanics of Backpack Load Carriage

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Summary

We biomechanically examined how backpack load and walking speed interact in their effects. 16 males walked under all 12 combinations of 6, 20, 33, and 47 kg backpack loads and 1.17, 1.33, and 1.50 m/s walking speeds. Generally, the effects of load were consistent over the speeds, and the effects of speed were consistent over the loads. Ground reaction forces and impulses, joint forces, muscle torques, muscle electrical activity and backpack acceleration increased when speed and/or load increased, likely increasing the probability of fatigue and injury. As load increased, percentage of stride in double-support and time of toe-off increased, and maximum hip angle decreased, likely improving stability and reducing stress on the musculoskeletal system. However, increases in walking speed tended to cancel these adaptations. At the lower speeds but not the highest one, stride frequency increased and stride time decreased when the load increased from 33 to 47 kg. Downward impulses for the major lower body joints increased with load carried, but decreased as walking speed increased. At the 1.33 m/s speed, but not at 1.50 m/s, a gait adaptation resulted in a less-than-expected impulse increase when the load increased from 33 kg to 47 kg. At the fastest walking speed, the volunteers could not further increase stride frequency to reduce stride length, increase stability, and reduce potential lower body stresses. Thus, it appears that soldiers should avoid, if possible, walking faster than 1.33 m/s (4.8 km/hr; 3.0 mi/hr) when carrying backpack loads approaching 47 kg (100 lb).

Introduction

While there has been much research on the biomechanics of human gait, only a small proportion of such research has specifically addressed load carriage. In 1981, Pierrynowski, Norman, and Winter (30) used cinematography to investigate variation in the mechanical energy levels of the body segments and efficiency of volunteers carrying five different backpack loads. Kinoshita and Bates (24) compared the effects on ground reaction forces of a standard backpack vs. a two-pack system, the latter of which distributed the load equally between the front and back of the volunteers. In another study, Kinoshita (23) reported significant changes from unloaded body posture and gait pattern when loads of 20% and 40% of body weight were carried, but less deviation from normal walking with a front/rear pack system than a standard backpack. Our laboratory compared the effects of a load carriage system that distributed the load between the front and back of the torso to the effects of a standard backpack on walking posture both before and after a fatiguing maximal speed 20 km road march (12, 16). We also compared various load carriage systems as to walking and running biomechanics among both male and female soldiers (17, 18). Electromyography has been used to evaluate muscle activity during walking, especially in the lower extremities (4, 6, 27). Yet most studies of load carriage have been physiological rather than biomechanical and have focused on metabolic response (2, 9, 11, 14, 21, 28, 32).

Many investigators have biomechanically analyzed unloaded human locomotion, using methodology that can be applied to the study of load carriage. They evaluated stride length (35, 36), joint forces and moments (5, 7, 22), joint ranges of motion (26), path of the center of pressure on the foot (15, 38), mechanical power (25, 41), external work (13), timing of gait events (38), braking impulse (29), and the effects of speed on mechanics (31). Electromyography (EMG) has been used to determine which muscles are involved in a physical activity, estimate their contraction intensity, and determine the muscle contraction sequence (3, 10, 33, 34, 40). Stulen and De Luca (37) used EMG frequency analysis to gain insight into the effects of fatigue on motor unit recruitment patterns.

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Most of the commercial and military backpack systems and other load carriage equipment available today have not been tested biomechanically. Application of quantitative biomechanical evaluation to loaded human locomotion can potentially contribute to the effectiveness of equipment evaluation and design. Thus, we undertook the study upon which this report is based in order to gather information on the effects of backpack load and walking speed on gait kinematics and kinetics. The goal was to expand the knowledge upon which recommendations concerning pack systems, physical training programs, and load carriage technique are based. It was anticipated that this could ultimately benefit people who engage in load carriage for whatever purpose by increasing load capacity and transport speed, lessening the likelihood of injury, improving efficiency, and decreasing perceived level of difficulty. We published two technical reports based on the study, one addressing the effects of backpack weight (19) and the other the effects of walking speed (20) on gait biomechanics. The purpose of this report is to provide a closer look into how load and speed interact in their effects.

Methodology

Volunteers

Testing took place at the biomechanics laboratory of the U.S. Army Research Institute of Environmental Medicine, in Natick MA. There were 16 male volunteers for the experiment, including military volunteers assigned for a tour of duty to the U.S. Army Natick Soldier Center, soldiers recruited for temporary duty as test volunteers, and military and civilian employees of the U.S. Army Research Institute of Environmental Medicine.

A nomogram for repeated measures (8) was used to estimate the sample size. To find the number of volunteers needed, a line was drawn from the inter-trial correlation coefficient through the desired effect size to the sample size scale. Inter-trial correlation coefficients of most dependent variables analyzed in the biomechanical study of load carriage were available from pilot study. The inter-trial correlation coefficients for most of the variables examined were higher than 0.60. For an inter-trial correlation coefficient of 0.60 with a moderate effect size of 0.5 and a two-tailed alpha level of 0.05, 13 volunteers were needed. Sixteen volunteers were recruited in order to provide for data lost by equipment malfunction or to make up for volunteers who might terminate testing prematurely.

Instrumentation

Force Platform System. Information from the force platform included forces exerted by the feet in the vertical, front-back, and left-right directions relative to the walker as well as the location on the platform of the foot center of pressure. Knowledge of the latter was essential for calculation of the moment about the ankle joint due to ground reaction force, and the subsequent calculation of torques about the knee and hip.

The model LG6-1-1 force platform from Advanced Mechanical Technology Incorporated (Newton, MA), measuring 0.61 by 1.22 m, was mounted on a steel frame to keep it rigid and isolated from external vibrations that might cause spurious output signals. The system was designed to emit voltage signals proportional to forces and torques exerted on the plate's surface, which include forces in the vertical, front-back and left-right directions and torques around orthogonal axes through the center of the plate oriented in the latter three directions. Center of pressure was calculated from the forces and torques, as specified in the AMTI force platform manual (1). The force platform and walking surfaces were made flush by locating the force platform at the center of a custom-built 15 m long wooden walkway. A model SGA6-3 amplifier system, designed for computer data acquisition, contained a six-channel amplifier with switch-selectable gains of 1000, 2000, and 4000 for each channel. Each channel also had a selectable low-pass filter with a 10 Hz or 1,050 Hz cutoff frequency and selectable precision bridge excitation voltages of 2.5, 5, or 10.

Accelerometer. A model EGAXT3-84-c-100 tri-axial accelerometer (Entran Devices, Fairfield, NJ) was mounted in the pack during load carriage. It emitted voltage signals proportional to pack acceleration in three orthogonal directions. This temperature compensated strain gauge accelerometer measured accelerations in the range of ±100 g in the vertical, left-right, and front-back directions. Built-in over-ranging protection prevented damage to the device. Because of a very high resonant frequency of 1,700 Hz, the accelerometer did not distort the accelerations characteristics of human movement.

Cinematography System. One LOCAM II camera from Redlake Corp. (Morgan Hill, CA), capable of filming speeds up to 500 Hz, was used to film the volunteers during load carriage. A frame rate of 60 Hz was used for this experiment to capture the body movements of interest. The camera incorporated a timing light that placed markers on the edge of the film every .01 sec to allow checking of film speed. A model 12-0101 battery pack permitted use of the camera away from AC power outlets. Model 9003-0001 floodlights (1000 watts) from Colortran (Burbank, CA) and model 18001 Mini-Mac photoflood lamps (1000 watts) from Bardwell & McAlister (Hollywood, CA) provided illumination.

For analysis, developed films were projected with an M-16C projection head from Vanguard Instrument Corp. (Melville, NY) onto an ACT23 digitizing table from Altek Corporation (Silver Spring, MD). The projector allowed one frame of the film to be seen at a time. Specific frames could be referenced using a digital frame counter. The digitizing table had a resolution of .01 mm and was connected via its controller to a model 486-33 IBM-PC compatible computer from Club American Technology Inc. (Fremont, CA). The experimenter used a pointing device to identify the major joint centers of the body on the film image. The digitizing device sent table coordinates of the joint locations to a computer, where programs processed the coordinate information to calculate kinematic variables that included body segment positions, velocities, and accelerations. The volunteer's body mass and data from a force platform were processed along with the kinematic data to produce kinetic information, which included the forces and torques at each body joint.

Electromyography System. "Utah" model surface electrodes with integral preamplifiers and band pass filtering systems from Motion Control Inc. (Salt Lake City, UT) were used to record muscle potentials from the shoulder, back and legs. Each electrode was factory calibrated, with individual gains ranging from 340 to 380. Although the gain was slightly affected by the frequency of the signal being amplified, the variation in gain for signals between 60 and 500 Hz was within 2% of the range. The bandwidth of the preamplifier was 8 Hz to 33 KHz. The high input impedance of the electrodes made it unnecessary to abrade the skin or use electro-conductive jelly.

Computerized Data Collection System. The data were sent to a model 486-33 IBM-PC compatible computer from Club American Technology Inc. (Fremont, CA), including six output signals from the force platform, three from the accelerometer, six from the muscle EMG electrodes, and one from the event marker, for a total of 15. The signals were fed into a model DAP1200/2 data acquisition and analog-to-digital converter board (DAP) from Microstar Laboratories Inc. (Redmond, WA) mounted in an expansion slot in the computer. The DAP combined analog data acquisition hardware with a 16-bit microprocessor and a real-time multitasking operating system. It had 16 channels, each of which could be specified in software as single-ended or differential.

The inputs to the DAP were voltages, which the board converted to numbers. The board could perform computations on the resulting numbers before the information was sent to the computer, making data processing very fast. The gain factor was independently software selectable for each channel, with possible values of 1, 10, 100, and 1,000. Allowable voltage input ranges with unity gain were 0 to 5 V, -2.5 to +2.5 V, -5 to +5 V, and -10 to +10 V. Maximum sampling rate was 50,000 per second. The sampling rate for this experiment was 1,000 Hz for all the channels except for the EMGs. Two logical channels operating at 1,000 Hz each were used for each EMG hardware channel, so that the actual sampling rate was 2,000 Hz per EMG channel.

Backpack. A backpack (Figure 1) was specially designed for the experiment, using a standard U.S. Army ALICE external pack frame as a base. Two metal shelves were added to the frame. On the bottom shelf was mounted a metal box containing the accelerometer, a terminal for the EMG electrodes, and a junction for a multi-conductor cable through which output data could be sent to the analog-to-digital converter board mounted in the computer. The top shelf of the pack was designed to hold weights so that the intended experimental loads could be carried in the pack. The weights were in the form of lead bricks and rectangular iron plates.

Figure 1. The instrumented backpack used in the experiment

An effort was made to match as closely as possible the location of the vertical center of mass of the experimental pack and an ordinary backpack. A pack loaded in standard fashion was balanced on a straight edge to locate its vertical center of mass. The weights were then arranged on the experimental pack in such a manner as to match the vertical center of mass location of the standard pack. Blocks of stiff foam were used as spacers on the shelf under the weights to make sure all of the pack loads had the same center of mass.

Two tape markers were placed on the side of the experimental pack so that the pack's position could be determined throughout a filmed trial by digitizing. The location of the actual pack center of mass relative to the markers was measured and recorded for use by the film analysis computer program.

Speed Cuing Device. A device to pace the volunteer's walking speed was designed at the U.S. Army Research Institute of Environmental Medicine and fabricated at the U.S. Army Soldier Systems Center in Natick, MA. It was based on a motor-driven cord marked with alternating light and dark bands that traveled around two pulley-wheels spaced 8 m apart. The speed of the cord was set using a dial. A digital display enabled cord speed to be set to the nearest 0.01 m/s. During an experimental trial, the device was oriented alongside the volunteer so that the visible part of the cord traveled in the direction the volunteer walked. The volunteer walked straight ahead while maintaining a peripheral view of the moving cord, which cued the appropriate walking speed.

Experimental Procedures

Independent Variables. Two independent variables were tested, backpack load and locomotion speed. The experiment was designed to test subjects under all 12 possible combinations of 4 backpack loads (6, 20, 33, and 47 kg) and 3 walking speeds (1.1, 1.3, and 1.5 m/s). The load of 6 kg was chosen because it was the weight of the backpack itself. The volunteers had to carry the pack even in the lightest load condition because the pack contained an EMG terminal as well as an accelerometer. The load of 47 kg was selected as a very heavy load that may be carried by serious backpackers and soldiers. The other two loads were equally spaced between the 6 and 47 kg loads. The 3 selected walking speeds can be respectively characterized as slow, medium, and fast.

Dependent Variables. The following variables were calculated from the vertical, front-back and left-right forces exerted by the feet on the force platform:

a. heel-strike and push-off peak forces (N)
b. time of occurrence of heel-strike and push-off peak force (percent of stride time)
c. peak and average front-back and mediolateral forces (N)
d. positive and negative vertical, front-back and mediolateral impulse per stride (N·sec)

Film analysis allowed calculation of the following:

a. joint ranges of motion for the hip, knee, and ankle (radians)
b. joint torques for the hip, knee, and ankle (N·m)
c. joint forces at the hip, knee, and ankle (N)
d. stride length (m)
e. stride frequency (strides/min)
f. single-support time (percent of stride time)
g. double-support time (percent of stride time)
h. body segment and center of mass position, velocity and acceleration

EMG analysis allowed calculation of the following:

a. peak and average muscle activities for the trapezius, spinal erector, quadriceps, hamstrings, gastrocnemius, and tibialis anterior muscles (uV)
b. timing of activation for the muscles listed above

Accelerometer data analysis allowed calculation of the following:

a. peak accelerations of the backpack in the vertical, front-back, and left-right directions (g)
b. timing and directions of the accelerations

Test Trials. All volunteers were orally briefed on the purpose, risks, and benefits of the study, after which they signed informed consent documents. Electrodes were attached to the volunteers' skin with adhesive tape after the skin was cleaned but not abraded with rubbing alcohol and a gauze pad. Electrodes were placed over the following muscles using anatomical landmarks according to the recommendations for standardized electrode positions (42):

- trapezius (elevates the shoulders, resists shoulder depression under the weight of the backpack)
- lower erector spinae, L4/L5 level (extends the back, resists forward movement of the trunk due to backpack weight and inertia)
- rectus femoris (extends the knee and flexes the hip during locomotion, helps lift the weight of body and backpack during the stride)
- biceps femoris (flexes the knee, extends the hip)
- tibialis anterior (works eccentrically to control the speed of foot plantarflexion so that the foot doesn’t hit the ground too quickly)
- gastrocnemius (plantarflexes the foot, helps lift the weight of body and backpack during the stride)

The volunteers performed their test trials (Figure 2) while wearing shorts and military boots. Prior to data collection, reflective tape markers were placed on the right side-view joint centers of the ball of the foot, ankle, knee, hip, shoulder, elbow, and wrist. Volunteers then donned the loaded backpack. Trials consisted of walks of no more than 15 m across the force platform in the camera field of view. Each volunteer was given practice trials to adjust walking speed and starting position so that the right foot landed squarely on the force platform as the volunteer walked across it. Occasionally, trials had to be repeated if the volunteer did not walk at the appropriate speed or did not place the foot completely within the confined of the force platform. A volunteer performed no more than nine trials in a test session (1 load x 3 speeds x 3 trials), with a maximum of two test sessions per volunteer per day (one in the morning and one in the afternoon). The volunteers were to walk at 1.1, 1.3, and 1.5 m/s corresponding to slow, medium, and fast walking with a backpack load, visually cued by the specially designed speed-cueing device running alongside the volunteer. However, later cinematographic analysis revealed that their actual speeds were respectively 1.17, 1.33, and 1.50 m/s (4.2, 4.8, and 5.4 km/hr; 2.6, 3.0, and 3.4 mi/hr), which still can be characterized as slow, medium and fast backpack load carriage speeds. Subsequent to this experiment, an electric-eye speed-trap system was added to the experimental methodology to provide immediate feedback as to whether the volunteer walked at the cued speed. Each volunteer carried a different load on each test day resulting in a total of 36 acceptable trials over four test sessions. Occasionally, a trial had to be repeated if the volunteer's foot did not land directly on the force platform. Adequate rest periods were allowed between trials to avoid fatigue as a confounding factor. Each trial lasted no more than 15 seconds, so total exercise time per day was minimal.

Figure 2. The experimental setup. For the trials, the volunteers wore boots.

Data Processing. Data were collected and analyzed on the computer. Programs in the C++ computer language, specifically written for the study collected the digitizing table coordinates from each frame of film, as well as the data from the six force platform channels, the three accelerometer channels, and the six EMG electrodes, all converted from analog signals to numerical information by the A/D board. Other programs performed the processing necessary to compute records of dependent variable values over the stride. A large statistical file then was created which contained key variables describing the gait patterns of all the volunteers.

The EMG data underwent digital-to-RMS conversion (33) and other interpretive procedures. The vertical and horizontal forces determined from the force platform divided by the weight of body-plus-load gave vertical, mediolateral and front-back accelerations of the system center of mass. Mathematical integration of the accelerations yielded velocities.

Digitizing. Of the 3 trials of each volunteer per load-speed combination, data from the one closest to the target walking speed was selected for statistical analysis. An experimenter obtained the x-y image coordinates of each marker on a volunteer's body over a full stride by projecting the film one frame at a time on the rear side of the translucent digitizing table and sequentially placing the cross-hairs of a transparent mouse-like device over the center of each joint marker image. When the experimenter pressed a button on the device, the x-y digitizer table coordinates of the marker were sent to the computer. A custom-written Borland C++ computer program collected film data from the digitizing table via an IEEE-488 interface board (Capital Equipment Corp., Burlington, MA) installed in one of the computer's expansion slots. The program drew a stick figure of the volunteer on the computer screen as the film was digitized to allow immediate detection and correction of gross digitizing errors. The computer displayed the name of each joint as it was to be digitized.

The ball of the foot, ankle, knee, hip, shoulder, elbow, wrist, and earlobe of the right side of the volunteer were digitized. The first frame digitized was 11 frames before the frame at which the right heel passed the back of the left lower leg. The last frame digitized was 12 frames after the right heel again passed the back of the left lower leg. This centered the gait data at right heelstrike, giving the best possible film images of the entire stride. The extra frames digitized at the beginning and end of the stride were needed for mathematical data smoothing and to ensure that a full stride was recorded. Before processing the film images from a given trial, the experimenter digitized the images of the four corners of the force platform, which were later used to calculate the film coordinates of the center of pressure, needed for the kinetic analysis.

Data Smoothing and Interpolation. The digitized film data were smoothed using Fourier analysis and Digital Filtering subroutines contained in Software for Science and Engineering Tools IPC-TC-006 (Quinn-Curtis, Needham, MA). The smoothed data were then processed with a cubic spline curve-fitting subroutine from the same software library to produce 101 interpolated frames for one full stride representing 0% to 100% of the time of a full stride. Thus, the results for each volunteer were in terms of percentage of stride. The actual time between interpolated frames was unique to each trial and was later used to calculate actual velocities and accelerations of the body segments and center of mass.

The mass, center of mass, and moment of inertia of each body segment were estimated using tables of standard body proportions based on dissection of cadavers (39). Because both heel-strike and toe-off were visible in the films and on the display of force platform data, these two points were used to time-synchronize film and force platform data. The EMG and accelerometer data were already time-synchronized with the force platform data because the computer's analog-to-digital converter board concurrently digitized them all. The foot's center of pressure location on the force platform's surface was calculated for each trial from force platform data using equations provided by the force platform's manufacturer (1). Joint moments and forces for the lower extremity were calculated using segment-by-segment kinetic analysis (39).

System of Postural Analysis. To analyze posture throughout the stride, the system of sagittal plane body angles shown in Figure 3 was used, in which:

A = Ankle angle: the absolute ventral angle between foot and shank. Because the foot segment endpoints were the lateral malleolus and ball of the foot, when the bottom surface of the foot was at 90° relative to the shank, the ankle angle was about 120°.

K = Knee angle: the absolute dorsal angle between shank and thigh.

H = Hip angle: the absolute ventral angle between thigh and trunk.

T = Trunk angle: the ventral angle between the trunk and a horizontal line.

E = Elbow angle: the absolute ventral angle between upper arm and forearm.

S = Shoulder angle: the angle between upper arm and trunk (plus means upper arm is in front of the trunk; minus means upper arm is behind the trunk).

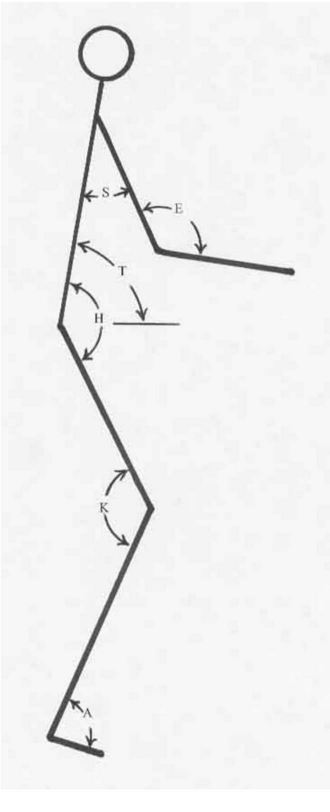

Figure 3. The system of sagittal plan body angles used to analyze posture throughout the stride.

Statistical Analysis. The large statistical file containing the key variables describing the gait patterns of all the volunteers was transferred to a VAX 780 main-frame computer where programs from BMDP (Berkeley, CA) were used for statistical comparisons between the different experimental conditions. Means and standard deviations for each variable under each testing condition were calculated. A 2-way analysis of variance with repeated measures was performed on each of the variables using the BMDP 2V program, with 3 levels of speed and 4 levels of load. Post-Hoc Tukey tests were employed to locate the differences between treatment means when significant treatment effects were found by analysis of variance.

Results and Discussion

Test Volunteer Characteristics

The test volunteers were all physically fit males, a bit above average in both height and body mass (Table 1). All engaged in regular physical activity. Of the 16 volunteers, 11 were enlisted U.S. Army personnel, three were Army officers, and two were civilian employees of the U.S. Army Research Institute of Environmental Medicine.

Table 1. Physical characteristics of the test volunteers (means +/- SD)

Age (yr)	30.3 +/- 9.2
Height (cm)	181.2 +/- 7.5
Body mass (kg)	76.8 +/-8.9
Gender	all male
n	16

Load Effects

We found several statistically significant ($p<0.05$) effects of backpack load on gait biomechanics. The following is a summary of the major load effects, descriptions of which can be found in much greater detail in our technical report on the effects of backpack weight on gait biomechanics (19).

The following increased significantly with increasing load:

stride frequency
time of toe-off as % of stride
percentage of stride under double-support
minimum knee angle
hip range of motion
forward trunk inclination
trunk range of motion
minimum horizontal velocity
propulsive impulse
peak and average propulsive force
% of stride at peak propulsive force
braking impulse
peak and average braking force
lateral impulse
average lateral force
medial impulse
peak and average medial force
vertical impulse
average vertical force
most of the peak bone-on-bone forces at the ankle, knee, and hip

most of the peak muscle torques about the ankle, knee, and hip
electrical activity of the trapezius, quadriceps, hamstrings, tibialis anterior, and gastrocnemius. It is noteworthy that the electrical activity of the spinal erectors decreased when the load increased from 6 to 20 kg, and only exceeded electrical activity at the 6 kg load when the load increased to 47 kg. This is likely related to the postural adjustments made with the different loads.
peak downward and backward backpack acceleration

The following decreased significantly as the backpack load increased:

stride time
knee range of motion
minimum hip angle
maximum hip angle
degree of rearward arm swing
degree of forward arm swing
shoulder swing range of motion
maximum vertical position
minimum vertical position

Within the range of walking speeds tested, the adjustments to increasing backpack load were consistent. Stride frequency increased as stride length tended to drop. Each foot stayed on the ground for a greater percentage of the stride, through increased hip range of motion, thereby increasing the percentage of the stride in double support. Arm swing decreased in both the forward and backward directions. The body as a whole stayed lower, mainly due to increased forward inclination of the trunk. With increasing backpack weight, the body didn’t slow down as much when the foot contacted the ground. These changes in gait with increased load can for the most part be regarded as positive adaptations. However, the increase in forces and torques at the ankle, knee, and hip, an inescapable consequence of carrying heavy loads, most likely increases the risk of musculoskeletal injury.

Speed Effects

There were three trials at each combination of load and speed, and preliminary film analysis was used to select the trial at each condition that came closest to the nominal speed. The volunteers deviated somewhat from the visually cued walking speeds of 1.1, 1.3 and 1.5 meters per second. They apparently had difficulty keeping their walking speed down to the slowest experimental pace of 1.1 m/s. Of the set of trials selected for final analysis, it was found that the volunteers cued to walk at the slowest speed of 1.1 m/s actually walked at 1.17±0.06 m/s. The volunteers cued to walk at the medium speed of 1.3 m/s walked only slightly faster than the cued pace, at 1.33±0.05 m/s. The volunteers cued to walk at the fast speed of 1.5 m/s were right on target, actually walking at 1.50±0.06 m/s. Because the actual walking speeds deviated from the cued speeds, the means of the three walking speeds differed by about 0.17 m/s instead of the planned 0.20 m/s,. Thus, the increases in speed from slow to medium to fast were in steps of about 13%-14% instead of the planned 15%-18%. Even though the walking speeds were not exactly as intended, they still corresponded to slow, medium, and fast load carriage speeds and likely represented a natural range of speeds for soldiers marching with backpack loads. Subsequent to this experiment we added an electric-eye speed trap to the system so that trials that deviated by more than 5% from the target speed could be rejected.

We found several statistically significant ($p<0.05$) effects of walking speed on gait biomechanics. The following is a summary of the major load effects, descriptions of which can be found in much greater detail in our technical report on the effects of walking speed on the biomechanics of load carriage (20).

The following increased significantly as load carriage walking speed increased:

- stride length
- stride frequency
- maximum ankle angle
- ankle range of motion
- maximum hip angle
- hip range of motion
- maximum shoulder angle
- shoulder swing range of motion
- maximum upward velocity of the body center of mass
- maximum downward velocity of the body center of mass
- vertical range of motion of the body center of mass
- propulsive impulse
- braking impulse
- lateral impulse
- average propulsive force
- average braking force
- peak propulsive force
- peak braking force
- peak lateral force
- peak upward-downward and forward-backward bone-on-bone ankle forces
- peak upward-downward and forward-backward bone-on-bone knee forces
- peak upward-downward and forward-backward bone-on-bone hip forces
- peak ankle dorsiflexion torque
- peak knee extension torque
- peak hip flexion and extension torque
- electrical activity of the trapezius, spinal erectors, quadriceps, hamstrings, tibialis anterior, and gastrocnemius
- peak upward, downward, and backward backpack acceleration

The following decreased significantly as load carriage walking speed increased:

- stride time
- time of toe-off as % of stride
- percentage of stride under double-support
- minimum hip angle
- minimum elbow angle
- degree of rearward arm swing
- minimum vertical position of the body center of mass
- medial impulse
- vertical impulse
- time of peak propulsive force as % of stride

It is noteworthy that trunk range of motion did not change at all with increases in walking speed. Also, average vertical force exerted by the foot on the ground increased less than 1% as walking speed increased 28% from the slowest to the fastest pace.

The adjustments to increased walking speed were consistent over the range of the backpack loads tested.
The 14% jumps in speed from 1.17 to 1.33 m/s and from 1.33 to 1.50 m/s were accompanied by 6-7% jumps in both stride length and stride frequency. The longer stride was effected both by reaching out further forward with the leg and pushing further backward with it, necessitating greater hip and ankle range of motion. This was accompanied by very large increases in hip extension and knee extension torque as well as large increases in hip flexion torque. Peak propulsive force occurred at an earlier percentage of stride. The importance of muscular work in extending the hips and knees to increasing walking speed was evidenced by an 83% increase in

hamstring electrical activity when going from the slowest to the fastest walking speed and a 40% increase in quadriceps electrical activity. All of the other muscles monitored increased in their electrical activity as well, although to a lesser degree. As the legs stretched apart during the longer stride, the body's center of mass dropped lower, thus traveling through a greater vertical excursion. Upward and downward velocity of the body increased. The degree of arm swing increased both towards the front and the back of the body, and the elbow bent more. It is important to note that because the toe lifted off the ground at an earlier percent of stride, the percentage of stride in double-support decreased, an effect opposite to that brought about by increasing the load. Increases in walking speed were brought about more by increases in horizontal than vertical forces. While propulsive, braking, and lateral impulses increased with walking speed, vertical impulse actually decreased. Average propulsive and braking forces increased over 20% from the slowest to the fastest walking speeds, but vertical force increased less than 1%. Despite the lack of increase in vertical ground reaction force with increasing walking speed, bone-on-bone forces increased in both the vertical and horizontal directions. With the backpack tested, peak accelerations of the pack increased with walking speed in all but the forward direction because flexibility in the strap system damped acceleration in that direction.

Combined Effects of Load and Speed

The fact that there were few statistical interaction effects of load and speed means that, for the most part, increases in load had the same effects on gait over the full range of walking speeds tested and increases in speed had the same effects on gait over the full range of backpack loads tested. As a result, the effects of speed and load were relatively uncomplicated. Many of the effects were in the same direction. For example increases in both speed and load resulted in increased joint torques. However, some of the effects of increasing load were opposite in direction to those of increasing speed, so that for certain variables, the effects of speed and load tended to cancel each other out. The following shows which effects were in the same direction for increases in speed and load, and which effects were opposite in direction. These combination effects are sub-categorized into those that have no apparent risk and those with possible attendant risks.

The following increased when speed and load increased, with no obvious attendant risks:

Stride frequency
Hip range of motion

The following increased when speed and load increased, with possible attendant risks:

Bone-on-bone forces and muscle torques: Greater forces pushing the bones together and pulling them apart probably increase the likelihood of injury to bones, articular surfaces, and ligaments. The greater muscle torques can be expected to increase the likelihood of muscle and whole-body fatigue and injury to muscles and tendons.

Propulsive, braking, and lateral impulses: As the product of force and time, impulse may be associated with muscle fatigue and injury to various tissues.

Propulsive, braking, and lateral forces: While we can't always determine whether an injury is the result of a single large force or repeated applications of smaller forces, higher force is more likely to result in tissue injury.

Downward and backward backpack acceleration: Acceleration is the result of force. Force on the backpack can be attributed to either gravity or the force exerted by the torso on the pack. Greater acceleration of the pack suggests greater reaction forces of the pack on the torso, applied to the shoulder straps or hip pad and belt, which may increase the likelihood of discomfort or injury to skin, nerves, and blood vessels.

Muscle electrical activity: Increases in muscle electrical activity are associated with greater force generation, which are associated in turn with increased fatigue and injury risk.

The following decreased when speed and load increased, with no obvious attendant risks:

Minimum vertical position
Minimum hip angle

There were no variables which both decreased when either speed or load increased and resulted in apparent attendant risk.

The following change in opposite directions with increases in speed and load, with no obvious attendant risks:

> Vertical impulse: Impulse, as the product of force and time, increases if either load or time increases. Higher backpack loads increase vertical impulse by increasing force, while increased walking speed reduces vertical impulse by shortening stride time.
>
> Arm swing: With increased load, the degree of arm swing lessens. Arm swing helps keep the torso from rotating excessively during walking by applying the increase in body angular momentum in the transverse plane, caused by off-center foot push-off forces, to the arms rather than to the torso. When the pack becomes heavier, it increases the inertia of the pack-torso combination. Angular momentum is the product of speed and inertia. Thus, since pack-torso inertia increases, the velocity of the torso for a given angular momentum decreases, reducing the need for arm swing to limit rotation of the torso. Increases in walking speed are effected by greater propulsive forces by the feet, which impart greater angular momentum to the body, in turn increasing arm swing for the reasons cited above. Thus, increased load and increased speed have opposite effects on arm swing. However, this has no apparent negative consequences.

The following changed in opposite directions when speed and load increased, with possible attendant risks:

> Percentage of stride in double-support and time of toe-off as percent of stride: An increase in these variables is considered a positive adaptation to increased load because it provides more stability and may reduce stress on the musculoskeletal system. However, as walking speed increases these measures decrease, tending to cancel the potential positive adaptations to increased load.
>
> Percent of stride at peak propulsive force: This measure increases as the load increases and decreases as the speed increases. The later occurrence of peak force as load increases may relate to earlier placement of the foot on the ground to increase double support time. The decrease in this measure with increased walking speed may represent a negation of this positive adaptation.
>
> Maximum hip angle: A decrease in this measure is related to a shortened stride and quicker cadence at increased load, a positive adaptation because it provides more stability and may reduce stress on the musculoskeletal system. However, increased walking speed counteracts this effect by lengthening the stride and increasing the hip angle as the foot pushes off, with possible increased risk.

Statistical Interactions of Speed and Load

There were a few variables exhibiting statistical interaction. That means that the effects of increasing speed were not the same for all loads and the effects of increasing load were not the same for all speeds. The variables showing such statistical interaction were:

Stride frequency: At the 1.17 and 1.33 m/s walking speeds, stride frequency increased markedly when the load increased from 33 to 47 kg. No such adaptation occurred at the 1.50 m/s walking speed.
Stride time: At the 1.17 and 1.33 m/s walking speeds, stride time decreased markedly when the load increased from 33 to 47 kg. No such adaptation occurred at the 1.50 m/s walking speed.
Downward impulses for shank-on-foot, thigh-on-shank, and trunk-on-thigh: Impulse, the area under the force vs. time curve over a full stride, increased with load carried, but decreased with increasing speed as stride time became shorter. The statistical interaction was due to the fact that the increase in impulse was directly related to pack weight except for the 1.33 m/s walking speed, for which the increase in impulse was less than proportional to the increase in pack weight when going from the 33 kg to the 47 kg pack.

All the above variables are related, accounting for the fact that they all showed statistical interaction in their responses to load and speed. Stride time and stride frequency are the mathematical inverses of each other. Since impulse is the product of force and time, impulses at the ankle, knee, and hip are sensitive to changes in stride time. The statistical interactions of stride frequency and stride time are related to the fact that, at the 1.17 and 1.33 m/s speeds, volunteers adapted to the heaviest load by taking shorter steps at a more rapid cadence, thus maintaining a stable base of support and avoiding excessive impulse about the lower limb joints. Yet this did not occur at 1.5 m/s, showing a lack of impulse-reducing gait adaptation to the heaviest load when walking at the fastest speed. The statistical interaction of the impulse variables is related to the fact that, at the 1.33 m/s walking speed, a gait adaptation occurred that didn't increase impulse as much as expected when increasing from the 33 kg to the 47 kg backpack. This adaptation did not occur at the 1.50 m/s walking speed. The lack of adaptation is likely related to the fact that, at the fastest walking speed, the volunteers could not further increase their stride frequency in order to shorten stride time. Without a reduction in stride time, an impulse increase could not be moderated.

Conclusions

It is clear from the study results that increasing either load or speed results in increased stress to the musculoskeletal system, as evidenced by bone-on-bone forces, ground reaction forces and impulses, and muscle electrical activity, which most probably increases the rate of fatigue and risk of injury. These effects are for the most part additive, as evidenced by the small percentage of variables showing statistical interaction, indicating that the effects of increased load are the same regardless of walking speed, and the effects of increased walking speed are the same regardless of backpack load. Thus, the combination of fast walking and heavy load can present a relatively high level of risk for fatigue and injury. The few variables that showed statistical interaction provided even more evidence that the combination of fast walking speed and heavy load can be particularly risky. At the fastest walking speed, 1.5 m/s (5.4 km/hr, 3.4 mi/hr), the volunteers could not shorten their stride length and increase their stride frequency when the load increased from 33 kg to 47 kg as they did at the slow and medium walking speeds (1.17 and 1.33 m/s). Their inability at the fast walking speed to make this adaptation to increased load means they could not effectively increase their stability and reduce the potential stresses to their legs and feet. It thus appears prudent to recommend that soldiers should avoid, if possible, walking faster than 1.33 m/s (4.8 km/hr; 3.0 mi/hr) when carrying backpack loads in the vicinity of 45 kg (100 lb).

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The Effect of Load Carriage on Trunk Coordination during Treadmill Walking at Increasing Walking Speed

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Summary

The purpose of this experiment was to determine the effects of walking speed and wearing a backpack on trunk coordination and upper and lower body angular momentum. Twelve subjects (5 male, 7 female, mean age, yr: mean±SD = 26±7.1) walked on a treadmill at increasing speeds from 0.6 $m \cdot s^{-1}$ to 1.6 $m \cdot s^{-1}$ in 0.2 $m \cdot s^{-1}$ increments. Subjects walked with a backpack (BP) containing 40% of their body mass and with no backpack (NBP). Peak pelvic and thoracic angular velocities were measured, and peak upper body and lower body angular momentum and the relative phase between the pelvis and thorax were calculated. A Repeated Measures ANOVA with two within-subject factors (load and speed) was used to compare the dependant variables. A significant main effect of BP condition was found in pelvic ($p < 0.0001$) and thoracic ($p < 0.0001$) angular velocities, upper ($p < 0.0003$) and lower ($p < 0.0001$) body angular momentum, and relative phase ($p < 0.0014$). In addition, a significant main effect of walking speed was found in thoracic angular velocity ($p < 0.0001$), pelvic angular velocity ($p < 0.0001$), upper body angular momentum ($p < 0.0001$), lower body angular momentum ($p < 0.0001$), and relative phase ($p < 0.0001$). A significant interaction effect between speed and load was determined for thoracic angular velocity ($p < 0.0001$), upper body angular momentum ($p < 0.0006$), and relative phase ($p < 0.0001$). There were higher pelvic and thoracic angular velocities, and higher upper and lower body angular momentum in the NBP condition compared to the BP condition. In the NBP condition, relative phase between pelvic and thoracic rotation increased from 54° at .6 $m \cdot s^{-1}$ to 122° at 1.6 $m \cdot s^{-1}$. In contrast, the increase in relative phase in the BP condition was less, from 48° at .6 $m \cdot s^{-1}$ to 78° at 1.6 $m \cdot s^{-1}$. With the addition of the BP, the decrease in thoracic angular velocity observed was disproportionate to the increase in the moment of inertia of the upper body caused by the addition of the pack, resulting in lower upper body angular momentum compared to the NBP condition. The lower upper body angular momentum in the BP condition may have occurred as a means to reduce the muscular force required to rotate the thorax, and hence lowered the metabolic cost of the increased load.

Introduction

Load carriage research performed at the United States Army Research Institute of Environmental Medicine (USARIEM) is designed to investigate how different physical properties of a backpack affect the individual carrying the load. Generally this approach involves isolating and manipulating a specific property of the backpack such as mass, volume, moment of inertia, or position of the center of mass (COM). The next step is to determine how manipulating this property affects variables such as metabolic cost, joint reaction force, and performance measures. For instance, Obusek (4) determined that when the COM of the backpack was high and close to the body, there was a reduced metabolic cost and lower limb joint reaction force. The purpose of the current experiment was to investigate the effects of walking speed and wearing a backpack on transverse plane thoracic and pelvic angular velocity, the angular momentum of the upper and lower body, and trunk coordination across different walking speeds. This study provides the basis for future work to determine the effect of load distribution on the individual carrying the load.

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During unloaded walking, increasing walking speed has been shown to affect parameters of gait such as hip excursion, stride length and stride frequency. Previous research has demonstrated that increasing walking speed is associated with increases in transverse plane pelvic rotation, transverse plane thoracic rotation, and trunk rotation (8, 9). In addition, Wagenaar and Beek (8) showed that at walking speeds less than approximately 0.8 $m\cdot s^{-1}$, the pelvis and thorax rotated in the same direction in the transverse plane (in-phase), while at higher walking speeds (> 1.0 $m\cdot s^{-1}$) the pelvis and thorax rotated in opposite directions (out-of-phase). Literature suggests (5, 9) the out-of-phase pattern between pelvic and thoracic rotation at walking speeds greater than 0.8 $m\cdot s^{-1}$ reduces the net angular momentum of the body.

Researchers have shown that stride frequency and transverse plane pelvic rotation increased with increasing walking speed (9). Taken together these suggest higher levels of pelvic angular velocity would result from higher walking speeds. In addition, it has been shown that due to a larger hip excursion and leg swing, the moment of inertia of the lower body increases at higher walking speeds (6). Because angular momentum is the product of angular velocity and moment of inertia, it was expected that lower body angular momentum would increase with increasing walking speed. Our first hypothesis was that increasing walking speed would cause an increase in pelvic angular velocity and lower body angular momentum.

Adding a backpack increases the moment of inertia of the thorax. Consequently, when carrying a backpack, less thoracic angular velocity will result in comparable levels of upper body angular momentum as when not carrying a backpack. If the thorax rotates in order to counter balance the angular momentum of the lower body, a decrease in thoracic angular velocity is expected in the backpack condition. Therefore, it was hypothesized that during load carriage there would be a reduction in thoracic angular velocity in order to maintain comparable levels of upper body angular momentum, as when not wearing a backpack.

By adding a backpack that makes contact only with the thorax, we did not change the moment of inertia of the lower body. Because an increase in pelvic angular velocity was expected to result from increasing walking speed, an increase in lower body angular momentum was also expected. Similar increases in pelvic angular momentum were expected when carrying a backpack as when not carrying a backpack. Previous research has suggested as lower body angular momentum increases, there is a transition from an in-phase to an out-of-phase pattern between pelvic and thoracic rotation. In the present study it was hypothesized that increasing walking speed would cause a transition from an in-phase to an out-of-phase pattern of pelvic and thoracic rotation regardless of whether or not the subject was carrying a backpack.

Methodology

Volunteers

Fourteen healthy subjects participated in the study. Two subjects were excluded from the final analysis because of technical problems during data collection. The remaining five male and seven female volunteers were used in the final analysis. Subjects were (age, yr: mean±SD = 26±7.1) from the Boston University community, participated in strenuous physical exercise at least three times per week and had no orthopedic disorders or complicating medical histories. Prior to participation, subjects gave informed consent in accordance with the policies of the Boston University Institutional Review Board.

Experimental Procedures

Anthropometric Measures. Data were collected in the Barreca Musculoskeletal Laboratory at Boston University. Prior to data collection, anthropometric measures were taken of total leg, shank, thigh and arm length, as well as hip and shoulder width. Body mass and height were measured using a balance scale.

Experimental Protocol. Subjects walked with and without the backpack at six different speeds. The sequence of backpack or no backpack condition was balanced across subjects. Walking speed was increased from 0.6 $m\cdot s^{-1}$ to 1.6 $m\cdot s^{-1}$ in 0.2 $m\cdot s^{-1}$ increments, and then decreased in the same manner. There were a total of 6 speed conditions for each of the 2 backpack conditions. Subjects walked at each speed for approximately 3 minutes. During the last 30 seconds, kinematic and kinetic data were collected.

Instrumentation

Kinematic and Kinetic Data Collection Systems. Three-dimensional kinematic data were collected at 100 Hz through an Optotrak 3020 System (Northern Digital Inc., 403 Albert Street, Waterloo, Ontario, Canada, N2L 3V2). Cameras were placed on each side of a treadmill, approximately 3 meters from the treadmill. Subjects walked on an instrumented Kistler / Trotter treadmill (Gaitway model; Kistler Instrument Corporation, 75 John Glenn Drive, Amherst 14228-2171) capable of measuring vertical ground reaction force (VGRF). On average, the belt speed varied .01 $m \cdot s^{-1}$ (< 2%) within a speed condition regardless of load. The Optotrak system unit provides an external trigger that was used to trigger the start of the force plate data collection, thereby synchronizing the kinematic and kinetic data.

Optotrak required the use of infrared light emitting diodes (IREDS), which were placed bilaterally on the subject's zygomatic processes, acromion processes, mid thighs, lateral femoral condyles, lateral malleoli, and ulnar styloid processes. Transverse pelvic and thoracic rotations were recorded, using two custom made T-squares (9). IREDS were placed on each end of the T-squares (Figure 1). IREDS were also placed bilaterally on the center of mass of the backpack in the sagittal plane, and on the ends of the bar holding the weight.

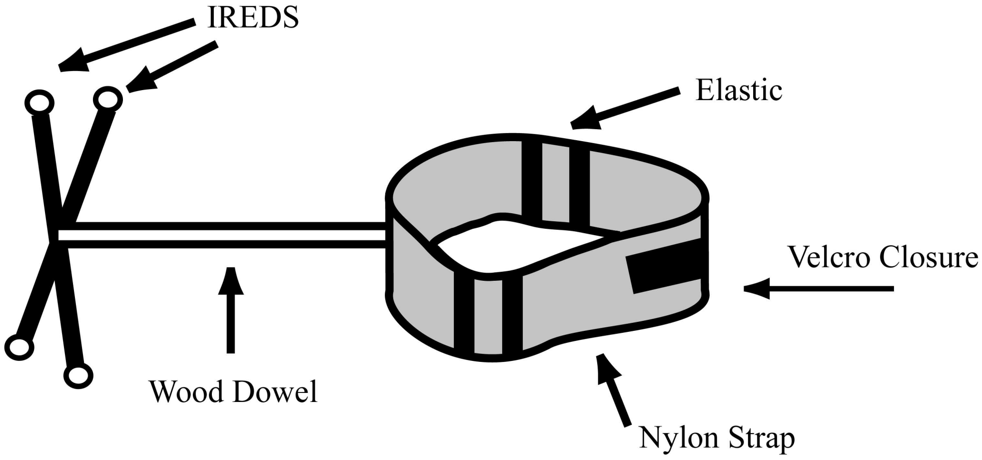


Figure 1. T-Squares

Backpack. The backpack frame was constructed of rigid plastic and designed to make contact only with the thorax (Figure 2). An aluminum rod was attached to the frame to hold a disk shaped weight at shoulder height as close to the subject as possible. Two adjustable shoulder straps and a mid thoracic strap minimized pack movement in relation to the thorax. The total weight of the backpack was adjusted to 40% of the subject's body weight. The weight was chosen to fall in the range of weights normally tested in backpack experiments (2, 4, 7).

DATA PROCESSING

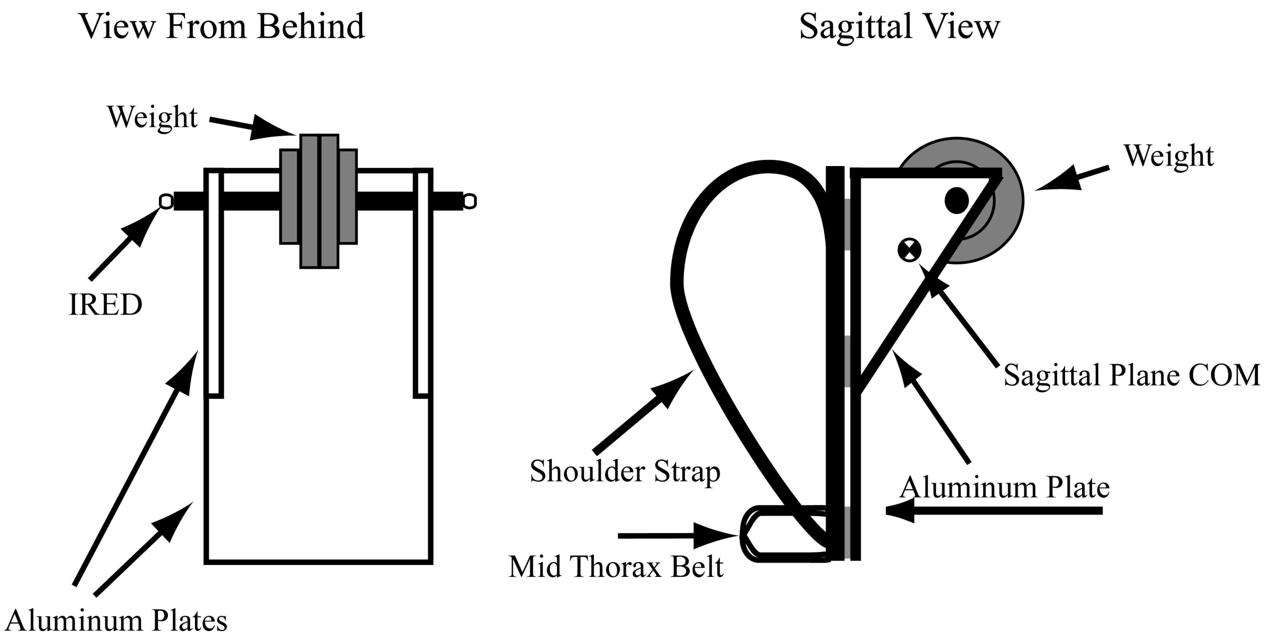


Figure 2. Backpack

Heel strike was determined as the first frame of the time series that the VGRF was greater than 7% of the peak VGRF. Toe off was determined as the last frame of the time series that the VGRF was greater than 7% of the peak VGRF (1). Heel strike and toe off data were used to calculate stride length and frequency.

The raw kinematic data were converted into 3D data by means of the Optotrak system software. Missing data were interpolated using a cubic spline. If there were more than 15 consecutive frames of missing data within any particular stride, that stride was discarded because the interpolation was not reliable. The interpolation procedure was validated against known values before its use and demonstrated a maximum error of 1.0 mm. Aberrant force-plate data would occur if both feet were on the same force-plate at the same time. There were a total of 4753 strides of data collected, of which 3.9% were eliminated due to missing kinematic or aberrant force-plate data. After interpolation, the data were filtered at 5 Hz (low pass second order Butterworth). Pelvic and thoracic rotations in the transverse plane were measured from the interpolated and filtered time series. Angular velocity was calculated from the displacement data. The transverse plane axis of rotation of the pelvis was assumed to be located at the spine, midway between the greater trochanters of the left and right hips. The transverse plane axis of rotation of the thorax was also assumed to be located in the spine, midway between the shoulders.

The moment of inertia of the upper and lower body were calculated using equation 1:

$$MoI = \sum_{i=1}^{n} m_i r_i^2 \qquad (1)$$

m is the mass of the segment. r represents the distance between the center of mass of that segment and the axis of rotation and n represents the number of segments. Segment mass and the position of each segment's center of mass were based on anthropometrics and calculated from estimates given by Dempster (3). In the case of the lower body, there were 5 segments (n =5): 2 shanks, 2 thighs and the pelvis. The mass of the feet was included in the mass of the shank segments. In the case of the upper body, there were 3 segments (n = 3): 2 arms and the thorax. For the purpose of the moment of inertia calculation, the upper and lower arm was considered to be one segment. The upper body also included the mass of the head. The contribution of the backpack to the moment of inertia of the upper body was calculated using the parallel axis theorem. Reported values are peak angular velocity and angular momentum.

Relative phase was used as a measure of coordination between pelvic and thoracic rotation and was calculated using the method described in van Emmerik and Wagenaar (8). An in-phase pattern indicates the pelvis and thorax are rotating in the same direction, and an out-of-phase pattern indicates the pelvis and thorax are rotating in opposite directions. Relative phase was calculated in the interval between 0º – 180º. Although relative phase is a continuous variable, generally an in-phase pattern is characterized by relative phase values between 0º and 90º, while an out-of-phase pattern is characterized by relative phase values between 90º and 180º. Repeated measures Analysis of Variance (ANOVA) with two within-subject effects was used to test for the main effects of speed (six levels) and backpack (two levels) conditions on the dependent variables. If significant interaction effects of backpack and speed were found, data were subset by walking speed and a repeated measure ANOVA was used to test for main effects of backpack at each walking speed.

Results

Effect of Carrying a Backpack

There was a significant main effect of backpack condition on thoracic angular velocity ($p < 0.0001$), pelvic angular velocity ($p < 0.0001$), upper body angular momentum ($p < 0.0003$), lower body angular momentum ($p < 0.0001$), and relative phase ($p < 0.0014$). Averaged across walking speeds, walking with a backpack resulted in a 40% lower pelvic angular velocity and a 54% lower thoracic angular velocity.

Figure 3

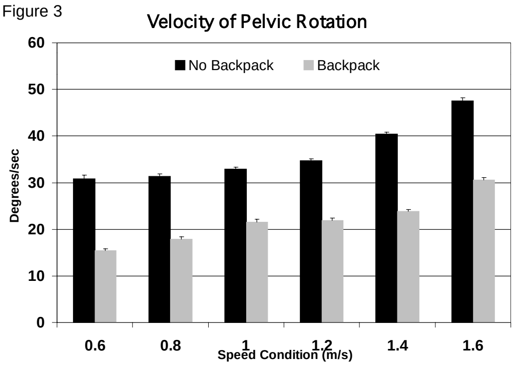


Figure 4

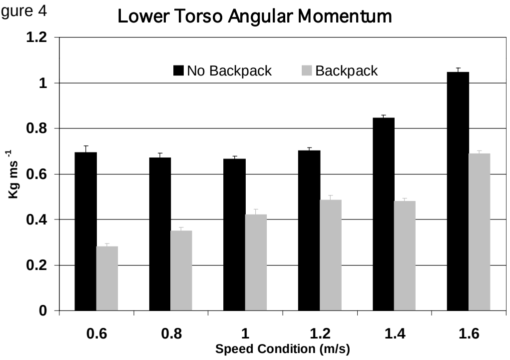


Figure 5

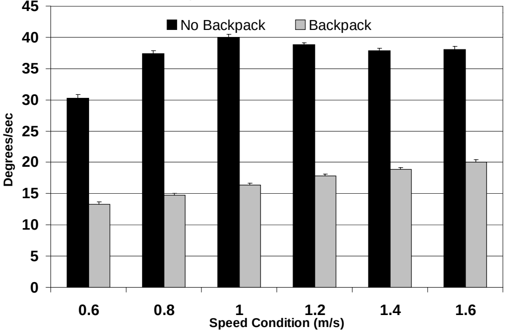


Figure 6

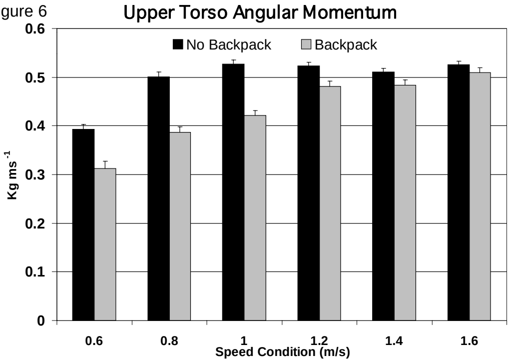
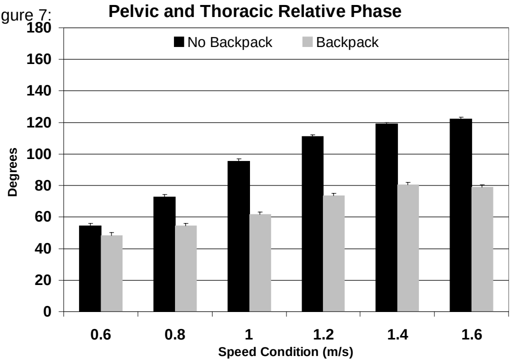


Figure 7:



Similarly, in the backpack condition there was a 38% lower upper body angular momentum and a 13% lower, lower body angular momentum. Adding a backpack resulted in a more in-phase pattern of relative phase (67.87º) compared to the no backpack condition (99.81º). Figures 3, 4, 5, 6, and 7 show the means and standard errors for thoracic and pelvic angular velocity, upper and lower body angular momentum, and relative phase across backpack conditions and walking speeds.

Effect of Walking Speed

A significant main effect of walking speed was found on thoracic angular velocity ($p < 0.0001$), pelvic angular velocity ($p < 0.0001$), upper body angular momentum ($p < 0.0001$), lower body angular momentum ($p < 0.0001$), and relative phase ($p < 0.0001$). Increasing walking speed from .6 $m \cdot s^{-1}$ to 1.6 $m \cdot s^{-1}$ resulted in a 39% increase in pelvic angular velocity, and a 23% increase in thoracic angular velocity. Similarly, lower body angular momentum increased 40% and upper body angular momentum 27% with increasing walking speed. In addition, at .6 $m \cdot s^{-1}$ the relative phase between pelvic and thoracic rotation was 51.78º, while at 1.6 $m \cdot s^{-1}$ the relative phase was 103.35º.

Interaction Between Walking Speed and Backpack Condition

A significant interaction effect between walking speed and backpack condition was determined for thoracic angular velocity ($p < 0.0001$), upper body angular momentum ($p < 0.0006$), and relative phase ($p < 0.0001$). No significant interaction between walking speed and backpack condition was found for pelvic angular velocity ($p < 0.1254$) or lower body angular momentum ($p < 0.0524$). Increasing walking speed in the no backpack condition caused significantly larger increases in thoracic angular velocity and upper body angular momentum compared to increasing walking speed in the backpack condition. In addition, increasing walking speed in the no backpack condition resulted in an increase in relative phase from 52º at .6 $m \cdot s^{-1}$ to 122º at 1.6 $m \cdot s^{-1}$, while in the backpack condition the increase was from 48º to 78º. When data were subset by walking speed, we did not detect significant differences in relative phase at .6 $m \cdot s^{-1}$ between backpack conditions ($p < 0.5076$); however, significant differences in relative phase were detected at 1.6 $m \cdot s^{-1}$ ($p < 0.0001$).

Discussion

In the present study we hypothesized that 1) increasing walking speed would result in an increase in pelvic angular velocity and increased lower body angular momentum; 2) wearing a backpack would result in lower thoracic angular velocity; and 3) increasing walking speed would cause a transition from an in-phase to an out-of-phase relationship between pelvic and thoracic rotation, regardless of backpack condition. Our results indicate increasing walking speed was associated with higher levels of pelvic angular velocity and lower body angular momentum, supporting our first hypothesis. In addition, carrying a backpack was associated with lower levels of thoracic angular velocity and a persistent in-phase pattern of pelvic and thoracic rotation compared to walking in the no backpack condition. Contrary to our predictions, no out-of-phase relationship between pelvic and thoracic rotation was observed in the backpack condition, and there was less upper body angular momentum compared to the no backpack condition.

Consistent with the findings of Wagenaar and Beek (9), increasing walking speed in the no backpack condition was associated with a transition from an in-phase to an out-of-phase relationship between pelvic and thoracic rotation. The transition occurred at walking speeds of approximately .8 $m \cdot s^{-1}$ to 1.0 $m \cdot s^{-1}$. In addition, increasing walking speed in the no backpack condition was associated with an increase in lower body angular momentum. Wagenaar and Beek have suggested that the pelvis and thorax rotate out-of-phase at higher walking speeds as a mechanism for reducing the net angular momentum of the body. When the pelvis and thorax rotate out-of-phase, high levels of lower body angular momentum are counterbalanced by high levels of upper body angular momentum in the opposite direction. However, the lower body angular momentum in the backpack condition at the highest walking speed was comparable to the lower body angular momentum in the no backpack condition at walking speeds, below which there was the transition to an out-of-phase pattern. This suggests the in-phase pattern of pelvic and thoracic rotation may be attributable to the lower level of lower body angular momentum in the backpack condition compared to the no backpack condition.

The decrease in thoracic angular velocity in the backpack condition was disproportionate to the increase in the upper body moment of inertia from the addition of the backpack mass, resulting in a decrease in upper body angular momentum. The larger moment of inertia of the upper body when wearing a backpack likely requires a greater degree of muscle force in order to rotate the upper body and to generate the angular momentum necessary to counter the opposing pelvic angular momentum. Consequently, maintaining an in-phase pattern between pelvic and thoracic rotation while walking with a backpack may result in a lower metabolic cost.

This study provides insight into the kinematic adaptations associated with carrying a backpack and their kinetic consequences, and offers hypotheses about the causes of these changes. The information can be used by designers to develop packs that reduce metabolic cost and improve soldier performance during load carriage. However, further investigation is needed in order to determine if metabolic cost is affected by changes in trunk coordination resulting from adding a backpack.

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The Effects of Load Weight: A Summary Analysis of Maximal Performance, Physiological, and Biomechanical Results from Four Studies of Load-Carriage Systems

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Summary

Data from studies of standard and prototype load-carriage equipment were analyzed to determine the effects of the weight borne by male and female load carriers on time to traverse a 3.2-km course at self-paced, maximal speed and on energy expenditure and kinetic and kinematic variables during externally paced walking at 4.8 $km \cdot h^{-1}$. The equipment configurations included fighting, approach, and sustainment loads, with masses varying from 12 kg to 50 kg. It was found that course completion times and energy expenditure were directly related to the weight carried. The effects of load weight on the kinematic and kinetic variables were more complex. They included evidence of adaptations in walking gait that are likely to aid the load carrier in maintaining stability and in absorbing the increased forces associated with increased load on the body.

Introduction

For purposes of planning and executing military ground operations, the items worn and carried by U.S. soldiers are divided into three configurations (Department of the Army, 1990). The fighting load configuration is the lightest in weight. It consists of mission-related equipment that is essential for immediate and short-term combat maneuvers. This configuration includes the clothing being worn, a helmet, a weapon, ammunition, water, a belt and a vest with pockets for carrying some of the equipment, and, possibly, an armor vest. A second configuration, the approach march load configuration, is intended for use during prolonged, dynamic operations, such as marching to an assault point. The approach load consists of the components of the fighting load plus other items typically carried in a backpack, such as rations, a poncho, and additional ammunition and water. The third configuration, the heaviest, is the sustainment load configuration. This configuration includes the components of the approach load plus other items, such as a sleeping bag, a change of clothes, and additional ammunition, water, and rations.

The guidelines provided to military commanders indicate that weights of the fighting and the approach load configurations should not exceed 22 kg and 33 kg, respectively. However, the components of the load configurations, and thus the weights carried by ground troops, are not prescribed by military policy. Rather, field commanders are responsible for determining the components of troops' loads after assessing mission requirements and related situational factors (Department of the Army, 1990). The multiple threats on the battlefield and the dependence of mission success on adequate supplies can result in commanders overloading their soldiers. Troops often undertake prolonged marches while carrying heavy loads and still must be capable of engaging in strenuous activities once the objective is reached.

Studies of the effects of load carrying on soldiers' performance have focused mainly on the energy cost of carrying the load (Goldman & Iampietro, 1962; Pierrynowski, Winter, & Norman, 1981; Soule, Pandolf, &

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Goldman, 1978). However, there is a growing body of work investigating the biomechanical aspects of load carriage (Kinoshita, 1985; Martin & Nelson, 1986; Pierrynowski, Norman, & Winter, 1981; Quesada, Mengelkoch, Hale, & Simon, 2000). In addition, some research has been done on the effects of carried loads on maximal performance, such as times to complete either a sprint (Martin & Nelson, 1985) or an obstacle course (Holewijn & Lotens, 1992; McGinnis & Tambe, 1963). Often, load-carriage research is undertaken for the purpose of examining the effects of the weight carried and the design of the carrying equipment on the performance measures of interest (Knapik, Harman, & Reynolds, 1996). Because of test participant availability and other logistical considerations, the number of different weights carried in a single study is typically limited to three or four (Harman, Han, Frykman, & Pandorf, 2000).

A series of four load-carriage studies was conducted recently at the Center for Military Biomechanics Research in Natick, Massachusetts. Each of the studies included measures of maximal performance, energy cost, and biomechanical variables, as opposed to focusing on any one measure. The principal purpose of the studies was to compare the effects of different designs of load-carriage systems on soldiers' performance. In addition, each system was tested using three different load weights. The four studies employed the same test protocol and the basic clothing worn by the participants was the same. Each study was a repeated measures design, with a participant being tested under each load condition. The pooled data from the studies provided an unusual opportunity to examine the effects of a number of different weights on an extensive array of variables. Pearson product-moment correlation coefficients (r) were calculated to determine the relationships between carried weight and individual dependent variables. Also, the method of least squares was applied to fit simple linear regression equations to the data. The findings from these analyses of the pooled data from the four load-carriage studies are presented here.

Studies Analyzed

Summary data on the characteristics of the test participants in the four studies are shown in Table 1. Throughout testing, the participants carried a demilitarized M16 rifle and wore combat boots, a helmet, a ballistic protective vest, and a field uniform consisting of a shirt and trousers. The load-carriage equipment was added to this basic outfit. Each of the load-carriage systems was tested in a fighting, an approach, and a sustainment load configuration. The weights carried in each study are shown in Table 2. The weights include clothing and all other items on the body. Additional information on each study follows.

- *LW I vs. ALICE* (Obusek & Bensel, 1997). The first-generation prototype of the Land Warrior system (LW I) was tested against the Army's current, standard load-carriage system, the All-Purpose Lightweight Individual Carrying Equipment (ALICE). With the LW I, a rigid metal case was worn on the back as part of each load configuration. With the ALICE system, a load was carried on the back only in the approach and the sustainment configurations. Participants in this study were 12 Army enlisted men, who were infantry troops assigned to an airborne division.
- *LW II* (Obusek & Bensel, unpublished study). The second-generation prototype of the Land Warrior system (LW II) was tested in this study. As in the first-generation version of the system, every load configuration included a rigid metal case that was worn on the back. Eleven enlisted men, all infantry troops, participated in the study. Nine of the participants also took part in the LW I vs. ALICE study.
- *MOLLE vs. ALICE* (Harman et al., 1999a). A prototype system, the Modular Lightweight Load-Carrying Equipment (MOLLE), was tested against the ALICE system. With both the MOLLE and the ALICE, the approach and the sustainment configurations included a backpack, whereas the fighting load configuration did not. Participants were 12 Army enlisted women, whose military occupations varied from the physically strenuous to the sedentary.
- *MOLLE vs. MLS* (Harman et al., 1999b). This study included the MOLLE and the Modular Load System (MLS), another prototype load-carriage system. With both systems, a backpack was worn as part of the approach and the sustainment load configurations, but not with the fighting load configuration. Eleven male enlisted soldiers participated in testing. Six of the men were infantry troops and the remainder had recently completed initial Army training, which was comprised of basic and advanced infantry training.

Table 1. Mean (and *SD*) of Test Participant Characteristics

Study	Height (cm)	Weight (kg)	Age (yr)
LW I vs. ALICE	175.19 (5.65)	75.20 (13.99)	22.0 (3.1)
LW II	175.08 (4.64)	78.34 (14.57)	22.4 (3.1)
MOLLE vs. ALICE	165.92 (6.50)	61.26 (6.72)	25.3 (5.3)
MOLLE vs. MLS	179.11 (5.09)	83.46 (12.20)	24.0 (4.7)

Table 2. Mean (and *SD*) of Weights Carried (in kg)

	Load Configuration		
System	Fighting	Approach	Sustainment
LW I	23.45 (0.89)	35.47 (2.39)	50.11 (2.71)
ALICE	14.66 (0.72)	23.41 (0.73)	37.54 (1.02)
LW II	20.42 (1.18)	32.68 (1.12)	49.29 (1.29)
MOLLE	13.05 (0.63)	26.84 (0.49)	40.16 (0.60)
ALICE	11.82 (0.39)	24.07 (0.51)	38.36 (0.52)
MOLLE	12.87 (1.53)	26.18 (1.67)	40.51 (2.05)
MLS	12.26 (1.58)	24.18 (1.75)	37.65 (1.76)

Maximal Performance Test

Participants were timed as they completed a 3.2-km course, which included several small hills and consisted of paved and dirt roads. Participants were instructed to complete the course as quickly as possible. Due to equipment problems, this test was not carried out in the LW II study. In the other studies, a participant performed one run of the course in each load configuration with each type of load-carriage equipment.

The combined data of the three load-carriage studies indicate that there is a moderately strong, positive relationship between run time and weight carried, $r(190) = +.56$, $p < .01$. About 30% of the variance in time to complete the 3.2-km course is accounted for by the weight ($r^2 = .31$). The run time data and the results of the regression analysis are presented in Figure 1.

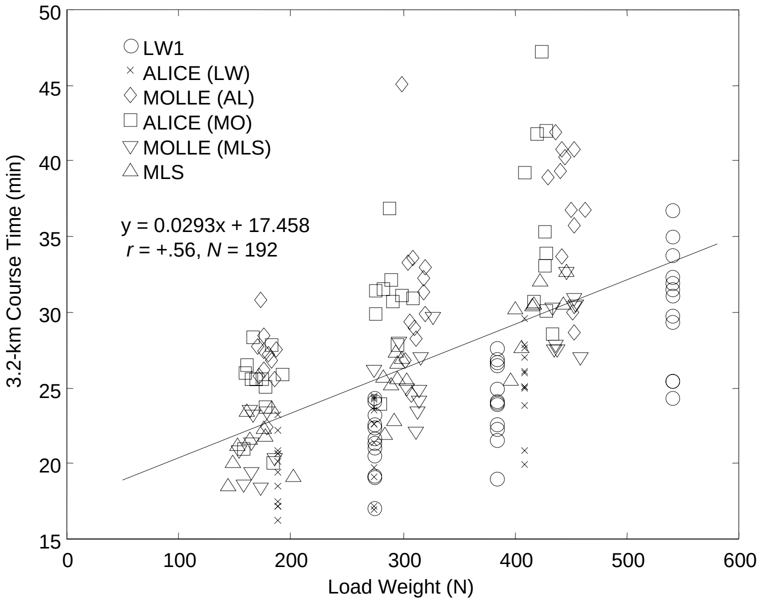

Figure 1. Scatter diagram and plot of simple linear regression equation for 3.2-km course time as a function of weight carried.

Energy Cost

Oxygen consumption was used as the index of energy cost. Test participants walked for 5 min on a level treadmill at a set speed of 4.8 km·h^{-1}. Oxygen consumption was measured at 30-s intervals during the last 1.5 min of testing. A mean was obtained over the three measurements and normalized by the participant's nude body weight. A participant had one trial in each load configuration with each type of load-carriage equipment.

The results of the regression analysis performed on the combined oxygen consumption data from all four studies are presented in Figure 2. The correlation coefficient indicates a positive and moderately strong relationship between energy cost and weight carried, *r*(228) = +.63, *p* < .01. About 40% of the variance in energy cost is accounted for by the weight (r^2 = .39).

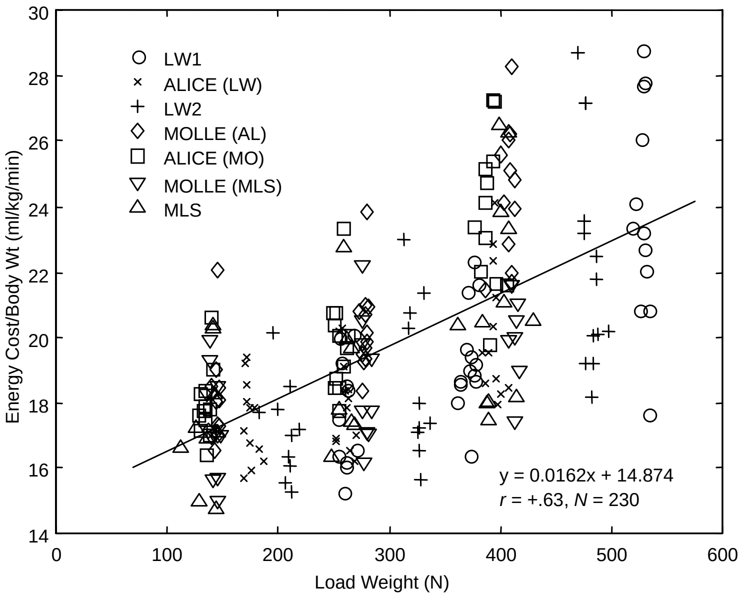

Figure 2. Scatter diagram and plot of simple linear regression equation for oxygen consumption normalized by body weight as a function of weight carried.

Biomechanics

Participants walked along a horizontal path at a controlled speed of 4.8 km·h^{-1} (± 0.2 km·h^{-1}). A force plate was mounted flush with the ground toward the end of the path. Data capture from the force plate was triggered manually about one stride before the right heel struck the plate. Force plate output was recorded for approximately 3 s at 1000 Hz. A video motion analysis system with six cameras, operating at 60 Hz, was set up in the area of the force plate. A complete stride, centered on the force plate, was analyzed from the video recordings. The body motions and the ground reaction forces were captured simultaneously. To quantify the biomechanics of walking gait, over 200 variables were measured directly or derived using customized software. The categories of kinetic and kinematic variables analyzed included ground reaction forces (GRFs), joint reaction forces, body angles, and temporal gait parameters. For the regression analyses involving the ground and the joint reaction force measures, the independent variable was system weight. System weight was defined as body weight plus the weight of the clothing and all other items on the body. The raw data entered into the regression analyses included the data from each of the trials that a participant performed in each load configuration with each type of load-carriage equipment. Depending upon the study, a participant performed from three to nine trials.

Ground Reaction Forces. The results of the regression analyses performed on the combined data of all four load-carriage studies revealed very high positive correlations between vertical GRF parameters and system weight. As an example, a scatter diagram and the best-fitting straight line for peak vertical GRF at heel strike as a function of system weight are presented in Figure 3. The r^2 value indicates that 88% of the variance in this parameter is accounted for by system weight (r^2 = .88). Correlations between some other GRF parameters and system weight are presented in Table 3, along with regression equations. As can be seen, braking and propulsive forces are highly correlated with system weight, but the correlations do not reach the values that those associated with vertical GRFs do.

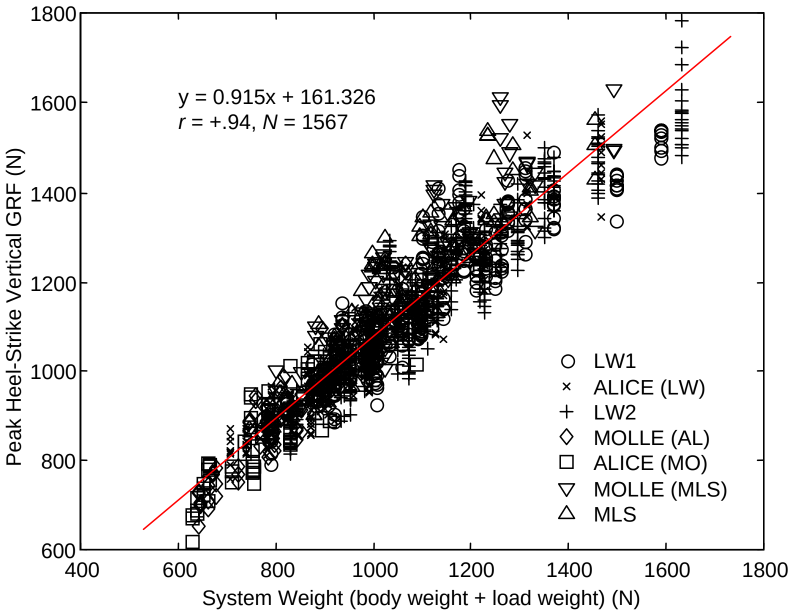

Figure 3. Scatter diagram and plot of simple linear regression equation for peak vertical GRF at heel strike as a function of system weight.

Table 3. Correlation Coefficients and Simple Linear Regression Equations for GRFs as a Function of System Weight

Variable	r^a	Regression Equation
Peak vertical force at push off	+.95*	y = 0.988x + 84.707
Peak braking force at heel strike	-.71*	y = -0.177x - 17.462
Peak propulsive force at push off	+.76*	y = 0.169x + 26.225

[a] $df = 1565$
*$p < .01$

Joint Reaction Forces. Joint reaction forces at the ankle, the knee, and the hip were calculated using the inverse dynamics method. Correlations calculated on the combined data of the four load-carriage studies revealed that both the maximum force and the force averaged over the stride are very highly and positively correlated with system weight. Table 4 contains a listing of correlation coefficients, along with regression equations, for the joint reaction forces.

The slopes associated with the regressions equations for the maximum forces at the joints are steep, approaching a 1-newton increase in the joint reaction force for each 1-newton increase in system weight. Also, the slopes of the regression equations for both the maximum and the stride-averaged joint reaction forces decrease from ankle to hip. Thus, the reaction forces at the more proximal joints increased at a less rapid rate with increases in system weight than did those at the more distal joints.

Table 4. Correlation Coefficients and Simple Linear Regression Equations for Joint Reaction Forces as a Function of System Weight

Variable	r^a	Regression Equation
Max. ankle joint force	+.96*	y = 0.982x + 125.198
Max. knee joint force	+.95*	y = 0.954x - 119.615
Max. hip joint force	+.94*	y = 0.899x + 107.584
Stride-averaged ankle joint force	+.98*	y = 0.470x + 19.138
Stride-averaged knee joint force	+.98*	y = 0.460x + 19.071
Stride-averaged hip joint force	+.98*	y = 0.443x + 18.357

[a] $df = 1565$
*$p < .01$

Body Angles. A number of body angles were calculated to analyze sagittal plane kinematics as affected by load weight. These are illustrated in Figure 4. For each body angle, the maximum, minimum, and range over a stride were obtained. Correlations of the body angle variables with weight carried were calculated from the combined data of the four load-carriage studies. The correlations are presented in Table 5.

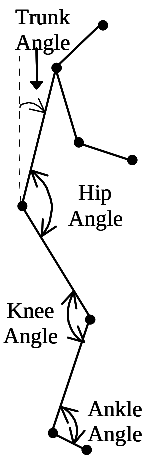

Figure 4. Definitions of body angles.

As seen in Table 5, there is a trend toward an increase in maximum ankle angle with increases in the weight carried. This finding most likely reflects an adjustment of body posture that aids in absorption of the increased GRFs at heel strike that are experienced as the load gets heavier. The increase in the range of ankle angle with increased load may be attributable to production of the greater propulsive forces needed to overcome the inertia associated with the increasing loads. The maximum knee angle and the range of knee angle decreased with increases in the weight carried. This increased knee flexion is likely to be another postural adjustment to load weight increases. Flexion at the knee improves shock absorption at heel strike and also lowers the body center of mass, making the body-plus-load system more stable. Maximum and minimum hip angles decreased and the range of hip angle increased with increases in the weight carried. The greater flexion at the hip may again aid in shock absorption. Maximum and minimum trunk angles increased with the weight carried, indicating an increased forward lean of the trunk. Trunk lean likely serves to move the center of mass of the body-plus-load forward over the base of support at the feet and also lowers the center of mass for additional stability.

Table 5. Correlation Coefficients for Sagittal Plane Body Angles and Weight Carried

	r^a		
Variable	Max.	Min.	Range
Ankle	+.13*	-.03	+.23*
Knee	-.09*	+.14*	-.23*
Hip	-.52*	-.68*	+.38*
Trunk	+.82*	+.80*	+.38*

[a] *df* = 1565 for all variables except maximum trunk angle and range of trunk angle, where *df* = 1561.
$*p < .01$

Temporal Gait Variables. Stride frequency was one of two temporal variables analyzed using the combined data of the four load-carriage studies. Stride frequency was estimated from a single stride and was expressed as strides·s^{-1}. The other temporal variable was double support duration, which was expressed as the percentage of time during the stride cycle that both feet were in contact with the ground simultaneously.

The results of the regression analyses performed on stride frequency and double support time are presented in Figures 5 and 6, respectively.

The correlations of the temporal variables with the weight being carried are low. The correlation between stride frequency and weight carried is negative, *r*(1565) = -.14, *p* < .01, and indicates a slight trend toward decreases in stride frequency, or an increase in time to complete a stride, with increases in load. Stride velocity is the product of stride frequency and stride length. In this study, stride velocity was held constant. Thus, the decreasing stride frequency also reflects a slight trend toward increasing stride length with increases in the weight carried.

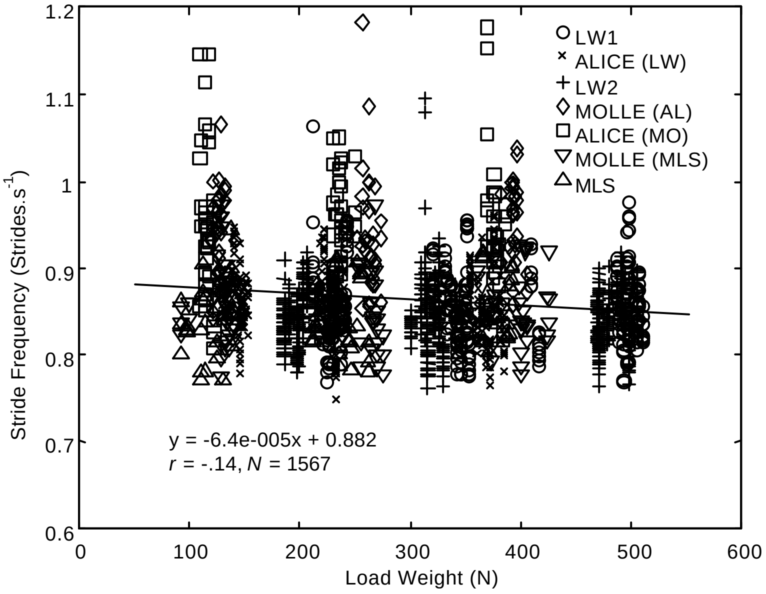

Figure 5. Scatter diagram and plot of simple linear regression equation for stride frequency as a function of weight carried.

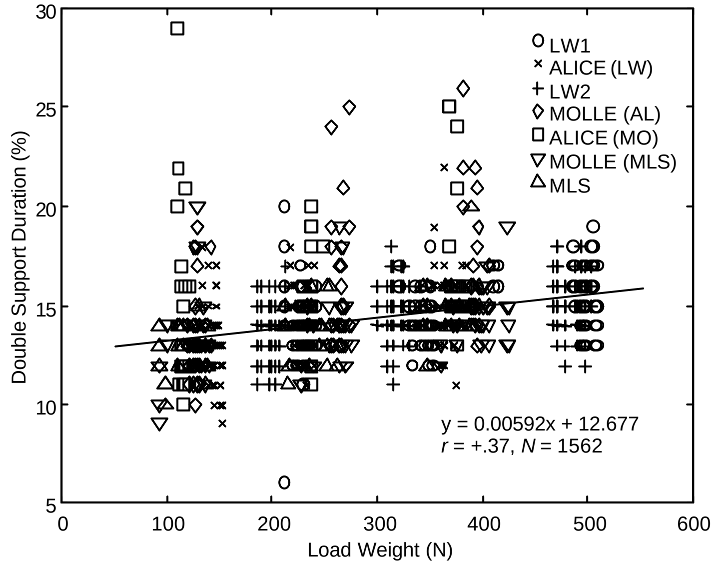

Figure 6. Scatter diagram and plot of simple linear regression equation for double support duration as a function of weight carried.

The correlation between double support duration and weight is positive, $r(1560) = +.37$, $p < .01$, and indicates that approximately 14% of the variance in double support duration is attributable to the weight carried ($r^2 = .14$). The increase in the proportion of the gait cycle spent in double support may be a means of maintaining stability with increases in load as the body should be more stable when both feet are on the ground than when one foot is in ground contact and the other is swinging forward in preparation for the next heel strike.

Discussion

As has been found in previous research (Martin & Nelson, 1985; Soule et al., 1978), the pooled data from the four load-carriage studies examined here revealed that soldiers' energy expenditure and times to complete activities requiring maximal performance increase with increases in the weight being carried. The linear regression analyses performed on the pooled data indicated that, for every 1 newton increase in weight carried, there was approximately a 3% increase in time to complete an outdoor course and a 2% increase in metabolic cost. Thus, carrying of heavy loads can result in a substantial negative impact on soldiers' mission performance and physical endurance. Furthermore, examination of the kinetics of walking gait revealed that heavy loads place a substantial burden on the load-carrier's musculoskeletal system. Regression analyses of the data from the four studies indicated that vertical ground reaction forces and joint reaction forces increased by approximately 1 newton with each 1 newton increase in system weight. The outcome of repeated exposure to these mechanical stresses associated with heavy loads can be the occurrence of acute and chronic injuries (Knapik et al., 1996).

From analyses of the kinematic variables associated with walking at 4.8 $\mathrm{km \cdot h^{-1}}$, it appears that postural adjustments made by the load carrier mitigate the forces to which the body is subjected and aid in maintaining stability. The pooled data from the four load-carriage studies revealed a trend toward greater flexion at the knee and the hip as the weight carried increased. Thus, the knee and the hip joints may be acting as shock absorbers. There was, as well, a more pronounced forward lean of the trunk as the load carried increased, a means of keeping the body center of mass over the base of support at the feet. Temporal gait measures were also affected by the magnitude of the load carried. With increasing weight, there was a slight trend toward fewer strides per unit time. In addition, a greater proportion of the gait cycle was spent with both feet on the ground. Other researchers have reported significant increases in double support time at higher load weights (Kinoshita, 1985; Martin & Nelson, 1986) and have hypothesized that this is also a means of increasing postural stability.

The research reported here, based upon data from four load-carriage studies employing an identical testing protocol, is unusually extensive, both in the many levels of load weight and in the variety of dependent measures included. However, there are, as well, limitations in the approach taken in this work. For one, simple linear correlation and regression analyses were employed, whereas curvilinear regression analysis may have provided more insight into the relationship of the weight carried and the dependent measures investigated. In addition, total load on the body was examined, and the manner in which the weight was distributed was not considered. Furthermore, different designs of load-carriage systems were used in the different studies, and analyses were carried out in the individual studies to assess design effects. However, the effects of system design and possible interactions between weight carried and system design were not investigated in the analyses of the pooled data reported here. Finally, the participants in the studies had not engaged in strenuous physical exercise prior to data-collection sessions. Soldiers in the field often carry loads for prolonged periods of time. Testing of soldiers under such conditions may lead to a fuller understanding of the impact of load weight on performance.

Conclusion

The weights soldiers carry have substantial negative effects on physical performance and endurance, as well as on the likelihood of injury. Postural adjustments are made to mitigate the negative consequences of heavy loads. A greater understanding of the implications of weight on military operations and the well-being of soldiers may be gained from the study of soldiers engaged in prolonged periods of load carrying.

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Correlates of Obstacle Course Performance Among Female Soldiers Carrying Two Different Loads

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Summary

To examine correlates of obstacle course performance, 11 female volunteers (mean±SD: 25.3±5.5 yrs, 166±6.5 cm, 61.3±6.7 kg) negotiated an obstacle course (low hurdles, zig-zag run, low crawl, overhead horizontal pipe, wall, and sprint) with a 14 kg fighting load and a 27 kg approach load. Predictive variables included Army physical fitness test (APFT: pushups, situps, and 3.2 km run) scores, treadmill $\dot{V}O_{2\ max,}$ and anthropometric variables. For the 14 kg load, pushups and situps correlated moderately ($p<0.1$) with time to negotiate the low crawl and pipe. With the 27 kg load the APFT score correlated moderately with zig-zag and low crawl times, body height correlated ($p<0.1$) with hurdles and zig-zag times, and $\dot{V}O_{2\ max}$ correlated with zig-zag and pipe performance. Only 55% of wall traversal attempts with the fighting load and 27% with the approach load were successful, and 80% of pipe traversal attempts with the fighting load and 30% with the approach load were successful. Because so many volunteers could not negotiate these stations, times for the segments were not included in the analysis of total course time. Pushups ($r=-0.54$, $p<0.1$) and situps ($r=-0.62$, $p<0.1$) best predicted course time with the 14 kg load, while the APFT score ($r=-0.57$, $r<0.1$) best predicted time with the 27 kg load. Aerobic fitness and muscular endurance play important roles in obstacle course performance. As measures of these abilities, the total APFT score and its pushup and situp sub-scores can serve as field expedient predictors of obstacle course performance.

Introduction

A soldier must not only carry loads to a battlefield, but must sprint across obstacles on the battlefield while under fire. The ability to traverse the battlefield quickly is an important component of both individual survival and the effectiveness of the fighting unit. An obstacle course requiring movements similar to those on a battlefield presents various physical challenges not characteristic of road marching. A soldier's performance on a well-designed obstacle course is a good indication of the ability to get across a real battlefield quickly.

Studies by Jette, Kimick, and Sidney (7), Kusano, Vanderburgh, and Bishop (9), Bishop et al.(2) focused on the physiological determinants of performance on indoor obstacle courses but only in the unloaded condition. Bishop et al. (2) examined the relationship of obstacle course performance (OCP) to upper and lower body aerobic and anaerobic power, muscular strength and endurance, and anthropometric characteristics, and found low but statistically significant positive correlations between course time, body weight and % body fat (heavier and fatter people took longer), and a negative correlation of course time with $\dot{V}O_{2\ max}$ relative to body weight. The best three-variable multiple regression equation (% fat, body mass, Wingate arm peak power) from this study accounted for only 35% of the variance in course time.

Jette et al. studied the obstacle course performance of Canadian soldiers who were loaded with helmets, boots and a rifle, and found higher correlations than Bishop et al. (2). They found that better obstacle course times were associated with higher aerobic power, anaerobic power, absolute strength, and muscular endurance. Stepwise multiple regression analysis determined that these four variables accounted for 81% of the variance in obstacle course time. Jette et al. (6) and Kusano et al. (9) also found excess body fat to be a detriment to OCP.

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What distinguishes the study described in this paper from the above studies is that the volunteers negotiated the obstacle course carrying 2 different loads, the total obstacle course and each segment of the obstacle course were electronically timed and, unlike all the previous studies except that of Kusano et al. (9), our study used female soldiers as test volunteers.

We found it important to study the ability of women to perform combat-related tasks because 1) during basic training in the U.S. Army, all female recruits currently participate in load carriage marches and other combat maneuvers, 2) women have been well integrated into combat-support Military Occupational Specialties (MOS)s and they could easily become involved in combat if front lines shift, and 3) it is possible that ground combat MOSs may be open to women at some time in the future.

Methods

Subjects

The volunteers for this study were 11 female soldiers who were medically screened and from whom written informed consent was obtained prior to their participation. In the U.S. Army women are not currently allowed into ground combat units, so none were combat soldiers. Several had sedentary jobs, but most had jobs that were physically demanding, such as Military Police work. The data in Table 1 describes the volunteers who as a group were moderately lean women of average weight and stature.

Table 1. Descriptive Characteristics of Subjects

Variable	Mean ± SD	Range
Age (yr)	25.3±5.5	19.4-38.2
Body mass (kg)	61.3±6.7	52.5-72.0
Body fat (%)	25.7±3.22	20.6-31.5
Fat free mass (kg)	45.5±3.7	41.3-50.9
Height (cm)	166.0±6.5	154.7-174.8
Shoulder diameter (cm)	37.0±1.4	35.2-40.2
Hip diameter (cm)	32.2±2.1	29.6-36.7
Hip circumference (cm)	93.9±6.4	87.6-105.4

Load Carriage Conditions

Volunteers were tested while carrying two different loads, the fighting and approach loads. The fighting load weighed 14 kg and consisted of the battle dress uniform (BDU), boots, body armor, Kevlar® helmet, equipment belt, load-carriage vest, dummy grenades, ammunition magazines, and an M-16 rifle. The approach load included the fighting load plus 13 kg of weight in a backpack, totaling 27 kg. The backpack used in testing was the standard external-frame Army packs (Figure 1).

Figure 1. Fighting load (14 kg) Approach load (27 kg)

The location of the center of mass of a backpack has been shown previously to affect energy cost by as much as 24% (10). In that study the best placement of the pack center of mass for minimizing the energy cost of load carriage was as close as possible to the center of mass of the person carrying the pack. That means the load should be as close to the persons back as possible and centered across the shoulder blades. The fighting load and approach load configurations were based on commonly used infantry loads. Once these configurations were established they remained unaltered for the duration of the study. The 3-dimensional location of the center of mass for each of these load conditions was determined using a balance board. The center of mass of the 14 kg load system was actually located 2-3 cm anterior of the subject’s chest. For the 27 kg load, the center of mass was slightly anterior of the frame of the backpack. These center of mass locations do not take into account the weapon carried in the hands in front of the body, which would bring the load center of mass even further forward.

Independent Variables

The independent variables in this study were maximal oxygen uptake, anthropometric measures and the U.S. Army’s physical fitness test.

Oxygen uptake was measured using a continuous, uphill, grade-incremental, treadmill protocol and a computerized open circuit spirometry system, which measured the rate of oxygen consumption and ventilation. The first test stage was a warm up with the volunteer running for 5 minutes at 5 miles per hour with the treadmill bed horizontal. After a 5 minute rest off the treadmill, the volunteer returned to the treadmill, donned the nose clip and mouthpiece for gas sampling, and started running on a 5% uphill grade at a speed determined to be moderate based on heart rate during the warm-up run. For the remainder of the test, the mouthpiece was kept in continuously and oxygen uptake was calculated every 30 seconds. Every 3 minutes the treadmill grade was increased by 2% without changing the treadmill speed. The test duration was typically 10-12 minutes.

The following anthropometric variables were evaluated as predictors of load carriage and obstacle course performance: age, height, body mass, biacromial and bitrochanteric diameters, hip circumference, percent body fat determined from skinfolds (4), and lean body mass.

All soldiers in the US Army are required to take the Army Physical Fitness Test (APFT) twice a year (3). The self-reported results of the volunteers' most recent physical fitness tests were analyzed to determine if they were useful predictors of obstacle course performance. The three components of the test are the maximum number of sit-ups completed in 2 minutes, the maximum number of push-ups completed in 2 minutes, and time taken to run 3.2 km. The absolute scores on the three subtests are assigned points that are scaled according to the soldier's age and sex, and these three subtest scores are added to get the total APFT score. An advantage of using APFT test data is that soldiers train for the test and are motivated to do well because a good score helps their chances for promotion.

Dependent Variables

The dependent variables for this study were the total time taken to complete the obstacle course and the times for each individual obstacle (Figure 2.). Subjects were timed negotiating a 6-station obstacle course with the 14 and 27 kg loads. The course was developed to evaluate the soldier's ability to traverse simulated battlefield obstacles rapidly while carrying combat equipment. An electronic timing system (Brower Timing Systems, Salt Lake City, Utah) was used to time the total course and each of the obstacles.

The volunteers began the course from a cued standing start with the first obstacle being a set of five 46 cm high plastic hurdles, spaced 2.1 m apart. The second obstacle required the subjects to run a zigzag pattern through a field of 9 plastic cones staggered such that adjacent cones were 1.5 m apart laterally and 3.4 m apart along the 26.8 m length of the course segment. Third was a low-crawl obstacle made of wood and rope, 61 cm high, 91 cm wide, and 3.7 m long. Without a backpack on, the volunteers could crawl on their hands and knees, but with a pack on they had to stay close to the ground and move along in a crab-like manner.

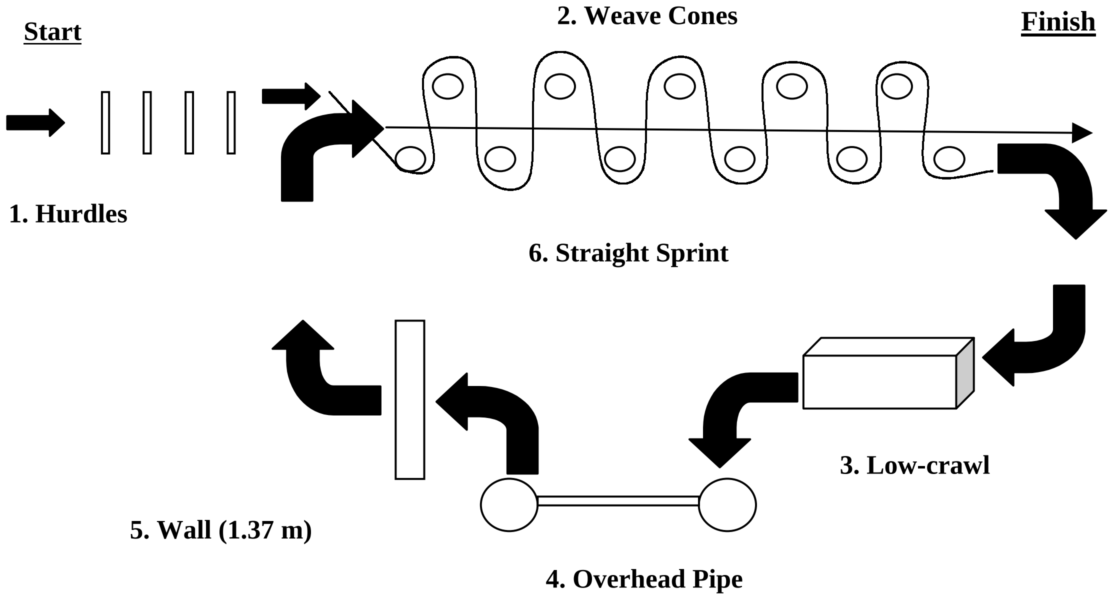

Figure 2. Plan of the obstacle course.

After the low-crawl, the volunteer proceeded to a horizontal pipe 3.7 m long suspended 1.42m above the ground. The subjects traversed the length of the pipe while hanging by their hands and feet. The majority of the weight was supported by the hands and arms, which also had to be used to pull the body along the pipe.

The importance of upper body strength became especially evident when the subject was wearing the heavier approach load. The legs provided some support, but mainly for the lower body. The pipe was divided into four equally spaced zones, and the last zone the subject reached was recorded. Because many of the volunteers could not completely traverse the pipe, the distance they traversed along the pipe before touching the ground, was also used to describe their performance. The fifth obstacle was a 137 cm high smooth wooden wall without footholds or ropes. The most common technique for getting up and over the wall was to place the hands on top of the wall and push down while jumping up high enough to get the torso and one leg on top of the wall, then dropping down over the other side. Spotters stood by to prevent subjects from landing headfirst. The movement involved mainly leg power. Since most attempts by the women to traverse the wall were failures, the criteria for judging performance on this obstacle was whether or not the volunteers succeeded at traversing the wall rather than the traversal time. Subjects finished the obstacle course with a 28.7 m straight sprint.

The test volunteers were instructed on how to complete each obstacle and given time to practice maneuvering through the various segments of the course. The test volunteers performed 2 trials with each of the 2 loads on the obstacle course with the presentation of loads balanced over the volunteers to eliminate order effects.

Results

Table 2 presents aerobic fitness and physiological performance data describing the test volunteers. The volunteers were more aerobically fit than the average female of their age according to normative data (1). $\dot{V}O_{2\ \mathrm{max}}$ (ml/kg/min) ranged from 41.9 to 54.4, which represents the 80-99th percentile for females age 20 to 29.The APFT score ranged from a low of 216 for the most sedentary individual to a high of 290 out of 300 possible points. Essentially this was a group of average sized, relatively lean, aerobically fit women.

Table 2. Physiological and physical performance characteristics of test subjects.

Variable	Mean ± SD	Range
$\dot{V}O_{2\ \mathrm{max}}$ (ml/kg/min)	48.8±4.6	41.9-54.4
$\dot{V}O_{2\ \mathrm{max}}$ (L/min)	3.0±0.5	2.4-3.7
3.2 km run time (min)	17.0±1.1	14.7-18.3
Push-ups (#)	41±12	26-64
Sit-ups (#)	68±10	54-85
APFT score (pts)	256±24	216-290

Obstacle Course Times

Table 3 shows the times to complete each station of the obstacle course with the 14 and 27 kg loads. It took subjects from 12 to 26 % longer to traverse the hurdles, zigzag, and straight sprint events with the 27 kg load than with the 14 kg load. The biggest difference was seen with the low-crawl obstacle, which took more than twice as long to negotiate with the 27 kg load than the 14 kg load.

The volunteers had a difficult time traversing the full length of the horizontal pipe obstacle and clearing the 137 cm high wall. While traversing the horizontal pipe with the 14 kg load, all but two of the subjects were able to complete the task in both of the trials they performed, and 80% of the trials were successes. With the 27 kg load the volunteers were only able to successfully traverse the full length of the pipe in 30% of the trials. On average, the subjects were only able to pull themselves to just over the halfway mark (57% of the length) of the pipe. Only 55% (6 of 11) of the subjects were able to make it over the wall with the 14 kg load and only 27% (3 of 11) cleared it with the 27 kg load. Because such a large percentage of subjects either took too long a time or were unable to complete these two obstacles at all, we removed the times for these two obstacles from the total course time.

Table 3. Obstacle Course Times (s)*

Obstacle	14 kg load		27 kg load		% increase in time with the heavier load
	Mean ± SD	Range	Mean ± SD	Range	
Hurdles	5.4±0.52	4.6 – 6.3	6.8±1.0	5.6 – 9.3	25.9
Zigzag	10.2±0.84	8.8 – 11.7	11.4±1.1	9.8 – 13.9	11.8
Low-crawl	12.2±2.3	9.0 – 16.8	25.3±6.3	16.2 – 37.5	107.4
Straight sprint	8.8±0.74	7.4 – 9.5	10.3±1.2	8.5 – 12.5	17.0
Course total*	36.5±3.6	30.3 – 43.1	53.9±8.4	41.7 – 73.1	47.7

* does not include the wall and pipe times

With the 14 kg load, taller volunteers were more successful at getting over the wall than were the shorter volunteers. Of the seven women who made it over the wall with the 14 kg load, six of them were the tallest in the group. Of the five women who made it over the wall with the 27 kg load, four of them were the tallest of the 11 volunteers. (As it turns out, it was not the same shorter subject who cleared the wall with both the 14 kg and 27 kg loads.)

Correlates of Obstacle Course Performance Time

The correlation coefficients of various independent measures with obstacle course time are shown in Table 4. It should be noted that, because a shorter time for the course or any of its segments indicates better performance, a negative correlation indicates that higher scores on that measure were associated with shorter times and, thus, greater speed.

Table 4. Correlates of Obstacle Course Performance Time

Obstacle	14 kg load	27 kg load
Hurdles	Hip diameter (r = 0.56)$^{\#}$ Hip circumference (r = 0.58)$^{\#}$	Height (r = -0.69)*
Zigzag run		Age (r = -0.66)* Height (r = -0.54)$^{\#}$ $\dot{V}O_{2\,max}$ (ml/kg/min) (r = -0.55)$^{\#}$ APFT score (r = -0.59)$^{\#}$
Low-crawl	Push-ups (r = -0.59)$^{\#}$ Sit-ups (r = -0.60)$^{\#}$	Sit-ups (r = -0.55)$^{\#}$ APFT score (r = -0.67)*
Pipe length completed	APFT score (r = 0.57)$^{\#}$ Push-ups (r = 0.58)$^{\#}$ Sit-ups (r = 0.64)*	$\dot{V}O_{2\,max}$ (ml/kg/min) (r = 0.55)$^{\#}$
Course total	Push-ups (r = -0.54)$^{\#}$ Sit-ups (r = -0.62)$^{\#}$	APFT score (r = -0.57)$^{\#}$

*$p<0.05$ $^{\#}p<0.1$

Hurdles. With the 27 kg load, greater body stature was associated with faster times over the hurdles (r=-0.69). This is likely related to taller individuals having longer leg length, and being able to more easily step over the hurdles. Individuals with longer legs would take fewer steps between hurdles, which could possibly result in faster times.

Zig-zag. None of the independent measures were significantly correlated with 14 kg load and time for the zigzag run. For the 27 kg load, age ($p<0.05$), height ($p<0.09$), relative $\dot{V}O_{2\ max}$ ($p<0.08$) and APFT score ($p<0.06$) correlated with zigzag run time.

Low-crawl. Volunteers who could do more push-ups ($p<0.06$) and more sit-ups ($p<0.07$) proved better at the low-crawl obstacle with the 14 kg load. Sit-ups again showed importance with the 27 kg load ($p<0.1$) as did APFT score ($p<0.03$). The large difference in completion time for the low-crawl between the two loads is probably due to a difference in crawling position. With the 14 kg load there was room to crawl through the obstacle up on the hands and knees. In regard to the upper body, the position of support for the crawl is nearly the same as when doing push-ups. Given this position, it is not surprising that pushup endurance proved a good predictor of performance. The low-crawl position used with the 27 kg load, the abdomen and chest were in direct contact with the ground allowing the subjects to maneuver beneath the roof of the obstacle. This movement technique was much more strenuous than that used with the 14 kg load and is probably one of the reasons why it took subjects more than twice as long to complete this obstacle with the 27 kg load than with the 14 kg load.

Because it was necessary for the subject's chest to be in contact with the floor they did not have to support their body mass using their upper body strength. Thus, upper body strength wasn't as important as it was with the 14 kg load. It is not surprising that pushup endurance did not correlate well with low-crawl time when carrying the 27 kg load.

Pipe. APFT score was a predictor of pipe performance with the 14 kg load ($p<0.07$). The fact that two-thirds of the APFT score is based on pushup and sit up performance, each of which is moderately well correlated with pipe obstacle performance (push-ups: $p<0.07$; sit-ups: $p<0.05$), accounts for the predictive value of the APFT score. The 3.2 km run component of the APFT score did not correlate well with pipe traversal time. With the 27 kg load, relative $VO_{2\ max}$ was the only variable to correlate well ($p<0.08$) with pipe traversal performance.

Sprint. None of the independent variables related well to the sprint segment.

Total course time. Subjects who did more push-ups ($p<0.09$) and sit-ups ($p<0.06$) had faster times for the total course with the 14 kg load. Higher APFT scores ($p<0.07$) were related to faster total course completion times with 27 kg load.

Discussion

A unique aspect of the study was the inclusion of two loaded conditions for assessing performance on the obstacle course. Muscular endurance scores, quantified as maximum number of push-ups and sit-ups performed, were the only independent measures that correlated well with obstacle course total time for the 14 kg load. For the heavier load, height, $\dot{V}O_{2\ max}$ and APFT score correlated fairly well with performance on some individual obstacles. The fact that $\dot{V}O_{2\ max}$ became a factor with the heavier load, when it wasn't for the lighter load, may be due to the fact that the heavier load lengthened course completion time to where aerobic metabolism accounted for a significant enough percentage of energy consumption.

Body fat was not found to be a major detriment to OCP. Neither percent body fat nor fat mass correlated significantly with obstacle course time. The findings of Kusano et al. (9) contrasted with ours in that they found body fat to be related to obstacle course performance. Their subjects ran their obstacle course unencumbered by external loads. The addition of loads in the range of 14–27 kg may be large enough to significantly alter the relationship that Kusano (9) found. While the subjects in our study would not be considered excessively lean, they were representative of the population of female soldiers at the end of the basic combat training course (% body fat =25.6, Sharp, et al.)(12) In addition, fat free mass and fat mass were positively correlated (r=.70); the volunteers who had greater fat mass also had greater fat free mass. For this reason, it is likely that subjects with greater fat mass were able to carry the extra fat without a decrease in performance compared to smaller, leaner subjects. Rayson et al. (11) also found in a pooled gender model that greater levels of body fat were associated with improved load carriage performance with a 15 kg load. However, because fat provides no benefit in itself to lifting or carrying heavy loads, it is likely that the subjects who did well carrying the backpack loads would do even better if they lost body fat, assuming that they could maintain their fat free mass.

The utility of total and component APFT scores for predicting obstacle course performance was apparent. With the 14 kg load, the greater numbers of push-ups and sit-ups performed were associated with faster times for the pipe, low-crawl, and total course. With the 27 kg load, a higher APFT score was associated with faster performance on the zigzag, low-crawl and total course. As components of the APFT, numbers of sit-ups and push-ups performed were related (r=0.60 for each) to APFT score. In contrast to other variables, the APFT variables maintained their association with low-crawl and total course performance across loads. There were two other independent measures that correlated with more than one course segment. With the 27 kg load, taller individuals performed better on the hurdle, zigzag, and wall obstacles (height was also important with 14 kg loaded wall performance); relative $\dot{V}O_{2\ max}$ correlated well with zigzag and pipe performance.

The fact that most of the correlations of the independent variables with OCP were only moderate in magnitude may be explained by the fact that the obstacle course involves a unique and complex blend of physiological, biomechanical, and mental abilities. Our findings in this regard agree with those of Kraemer et al. (8), and Bishop et al. (2). who suggested that high degrees of certainty for prediction of complex task performance might not be possible using a battery of simple anthropometric and fitness measures. Jette et al. (7) found higher correlations between aerobic power and OCP than we did. This may be due to the fact that the obstacles in their course of a much longer duration than ours.

In our previous studies men have not had a problem in clearing the wall (5). Based on body center of mass (COM) data by Winter (13) the female subjects had to raise their COM an average of 40 cm to clear the wall. In contrast it was estimated that the men only had to raise their COM 33 cm or 18% less than the females. Further examination of the COM location for the 27 kg load from this study and our earlier study with male volunteers reveals that the distance that women had to raise the load’s COM was 11.6 cm, whereas the men had to raise it only 1.8 cm. The women’s 27 kg load represented 44% of their body mass, and the men’s represented just 31% of their body mass. The women were at a considerable disadvantage compared to the men, with their body COM and the pack COM further below the top of the wall, combined with pack’s greater proportion of their body mass. It is clear that a volunteer tall enough has an advantage in wall clearing in that they would not need to be as strong in order to get their center of mass over the wall. As a result most women were unable to clear the wall.

Conclusions

The results of this study demonstrate that the APFT and two of its components, sit-ups and push-ups, which are measures of muscular endurance, showed predictive value for many of the obstacle course segments. This was true with both the light and heavy loads. Aerobic fitness and muscular endurance as expressed by the APFT score play important roles in obstacle course performance and could serve as field expedient predictors of obstacle course performance.

The other independent variables examined in this study, with the notable exception of aerobic fitness, and body stature, showed little or no predictive power. The complex nature of obstacle course performance makes it very difficult to use uncomplicated anthropometric, physiological or performance variables as stand-alone predictors of overall obstacle course performance.

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The Influence of Load Carrying Methods on Gait of Healthy Women

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Summary

Various load configurations on healthy men, but not women, have been examined. Women were found to have higher incidence of musculoskeletal injuries when carrying a heavy load during basic training. The purpose of this study was to examine the changes in gait patterns of healthy women while carrying a 10 Kg. load on the back, around the waist, and across one shoulder. The investigators further evaluated the influence of shoulder muscle strength on their gait with three load carrying configurations. Nine healthy women without existing orthopedic problems in the spine and legs were recruited for this study, ranging in ages from 22 to 32 years, with a mean of 25.2. Their height ranged from 148 to 179 centimeters, with a mean of 161.8. Their weight ranged from 45 to 74.1 kilograms, with a mean of 57.7. Fourteen reflective markers were placed on the subjects' trunk and legs. Two videocameras were used to film the subject walking along a 10 meter walkway. Each subject was first required to walk at her self-selected speed without any load to establish a baseline and then, in random order, walk with a 10-Kg. load on the back, around the waist, and diagonally across one shoulder. The videotape was analyzed using the Ariel Performance Analysis System. Angles of trunk, shoulder, hip, knee, and ankle were calculated. Torque output of subject's shoulder flexors, extensors, abductors, adductors, horizontal abductors, and horizontal adductors were measured on a Biodex II isokinetic dynamometer. Each subject was required to complete three sets of concentric contraction at 150 degrees/second. The total work for three contractions was normalized to each subject's weight. Analyses of variance with repeated measures were used to examine the influence of load carrying methods on gait. Multiple regression analyses were conducted to evaluate the influence of shoulder girdle muscle strength. Results: Subjects walked with significantly different trunk and shoulder angles ($p<0.001$) when walking with three load carrying configurations compared with the baseline and demonstrated the most rigid and flexed trunk when carrying the load on the back. Shoulder angles were significantly asymmetrical when carrying a load diagonally across one shoulder. There was no significant difference in hip, knee, and ankle angles. Shoulder girdle muscle strength strongly correlated with trunk and shoulder angles when carrying a load around the waist or on the back ($r^2=0.855$ to 0.989). Carrying a heavy load around the waist appeared to cause the least deviation from normal gait pattern for women. Women with strong shoulder muscles demonstrated less trunk and shoulder deviations when walking with a heavy load on the back.

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Introduction

Women in the military services were found to have a higher incidence of musculoskeletal injuries when carrying a heavy load during basic training (Ross & Woodward, 1994). Compared with males, females were of smaller stature, and had a wider pelvis, less upper body strength, and smaller feet and ankles. A variety of factors contributed to the high rate of musculoskeletal injuries among military women. Appropriate leg and trunk muscle strength appeared to be critical for women to function on jobs that required carrying loads and walking. Female military trainees with limited leg extensor muscle strength appeared to have a higher incidence of musculoskeletal injuries than female trainees with strong leg extensor muscle (Kowal, 1980). Reinker and Ozburne (1979) reported that poor design of female boots contributed to female trainees' high rate of musculoskeletal injuries during basic training. Various load configurations for healthy men, but not women, have been examined.

The purposes of this study was to examine the changes in gait patterns, heart rates, perceived rates of exertion, and discomfort of healthy women while carrying a 10 Kg. load on the back (using a backpack), around the waist, and diagonally across one shoulder. The researchers further evaluated the influence of should girdle muscle strength on their gait with three load carrying configurations.

Methods

Nine healthy, physically active women without existing musculoskeletal problems in the spine and legs were recruited for this study. Six subjects were physical therapists, one was a massage therapist, and two were full-time college students involved in exercise programs on a regular basis. Their ages ranged from 22 to 32 years, with a mean of 25.2 years. Their height ranged from 148 to 179 centimeters, with a mean of 161.8 centimeters. Their weight ranged from 45 to 74.1 kilograms, with a mean of 57.7 kilograms. The researchers obtained written consent and then conducted a screening examination to ensure each subject was free of musculoskeletal problems in the spine and legs. Fourteen reflective markers were placed on each subject’s head, trunk and legs. The markers were placed on the forehead and chin, and then bilaterally on the acromion processes, lateral sides of lower rib cage, greater trochanters, lateral femoral epicondyles, lateral malleoli, and lateral sides of the head of the fifth metartarsal bone. Two industrial level video cameras (Panasonic S-VHS AG-450, Secaucas, NJ 07094) were used to film the subject walking along a 10-meter walkway. One video camera was positioned in the frontal plane facing the walkway. The other video camera was positioned in the sagittal plane at a 60-degree angle to the walkway. Each subject first walked along the 10-meter walkway at her self-selected speed without any load to establish a baseline and then, in random order, walked along the walkway with a 10-kilogram load on the back, around the waist, and diagonally across one shoulder. The videotaped data were processed and analyzed using the Ariel Performance Analysis System (APAS) (Trabuco Canyon, CA 92679) at the sampling rate of 60 Hertz. The APAS calculated three-dimensional joint angles of the trunk, shoulder, hip, knee, and ankle.

Subjects then walked for one hour on a treadmill (Quinton 50) at 3.3 miles/hour with no load on the first day. Subjects then walked for one hour on the treadmill at 3.3 miles with the load using one of the three load configurations, assigned in a random order, on three consecutive days. Inclination of the treadmill was changed randomly every ten minutes, ranging from one to seven percent. Each subject followed the same treadmill protocol for the four testing conditions. While subjects were on the treadmill, the researchers monitored the heart rate, perceived rate of exertion, and discomfort every ten minutes. Heart rate (beats/minute) was monitored continuously using an ECG telemetry system (Physiodyne Instruments, Farmingdale, NY 11735). The modified Borg scale, ranging from one to ten, measured the perceived rate of exertion. A Visual Analog Scale, ranging from 0 (no paint) to 100 millimeters (the most intense pain), was used to measure the level of discomfort. Four testing conditions were conducted on four different days for each subject.

In the fifth session, each subject’s shoulder girdle muscle strength was measured by the Biodex II isokinetic dynamometer (Biodex Medical, Shirley, NY, 11967). The researchers followed the standard testing positions as recommended by the Biodex manufacturer to test each subject's shoulder flexors, extensors, abductors, adductors, horizontal abductors, and horizontal adductors bilaterally. After the warm-up routine, each subject completed three sets of contractions in the concentric mode, at 150 degrees/second, for each muscle group tested. The total work for three contractions was normalized to each subject's body weight to be used for data analysis.

The researchers used the Statistical Package for Social Science for Windows (version 10.0) to conduct statistical analysis. Analyses of variance with repeated measures were used to examine the influence of load carrying configurations on joint angles, heart rate, perceived rate of exertion, and discomfort. Multiple regression analyses were conducted to evaluate the influence of shoulder girdle muscle strength on gait.

Results

The researchers examined the trunk angle from the sagittal plane using the APAS to calculate the angle between the trunk markers and the horizontal line. A smaller trunk angle indicated more forward flexion of the trunk. Trunk angles were examined at heel strike, foot flat, midstance, heel off, and toe off points of the stance phase. See Table 1 for the mean trunk angles for the baseline and the three load-carrying conditions. Subjects showed most trunk forward flexion when carrying the load on the back. When subjects carried the load around the waist, their trunk angles were similar to those of the baseline condition. Trunk excursion angle was calculated as the absolute difference of trunk angle between heel strike and toe off. Trunk excursion angles varied significantly between the baseline measurement and three load-carrying configurations (p<0.001). Subjects showed the least amount of trunk excursion when carrying the load on the back (see Table 2).

Table 1. Mean Trunk Angles (degrees) during the Stance Phase of the Gait Cycle

	Baseline	Backpack	Waist*	Shoulder**
Stance Phase				
Heel Strike	103.53	89.13	100.79	98.51
Foot Flat	103.94	90.37	102.93	99.93
Midstance	97.76	86.72	94.4	95.04
Heel Off	94.09	84.17	91.31	92.68
Toe Off	95.75	87.66	91.31	96.17

*Waist – Carrying the load around the waist

**Shoulder – Carrying the load across one shoulder

Table 2. Mean Trunk Excursion Angles (degrees) during the Stance Phase of the Gait Cycle

	Trunk Excursion Angle (Degrees)*
Baseline	7.79
Backpack	1.48
Around the Waist	9.48
Across One Shoulder	2.34

* p<0.001

The researchers examined the shoulder angle from the frontal plane. The APAS used 180 degrees to represent the horizontal line. Numbers smaller or bigger than 180 indicated shoulder asymmetry. Shoulder angles were examined at heel strike, foot flat, midstance, heel off, and toe off points of the stance phase. Subjects showed the most shoulder asymmetry when carrying the load across one shoulder (see Table 3). The shoulder excursion angle was calculated as the absolute difference between the shoulder angle at heel strike and toe off. Subjects showed significant differences in shoulder angle between the baseline measurement and the three load carrying configurations (p<0.0009). They showed the least amount of excursion when carrying the load across one shoulder. Subjects showed similar shoulder excursion angles during the baseline condition and when carrying the load around the waist (see Table 4).

Table 3. Mean Shoulder Angles (degrees) during the Stance Phase of the Gait Cycle

	Baseline	Backpack	Waist*	Shoulder**
Stance Phase				
Heel Strike	177.88	179.1	177.16	176.92
Foot Flat	178.1	179.16	176.75	176.19
Midstance	180.09	180.62	178.88	176.89
Heel Off	181.07	180.95	180.37	177.34
Toe Off	181.66	181.32	181.05	177.17

*Waist – Carrying the load around the waist
**Shoulder – Carrying the load across one shoulder

Table 4. Mean Shoulder Excursion Angles (degrees) during the Stance Phase of the Gait Cycle

	Shoulder Excursion Angle (degrees)*
Baseline	3.78
Backpack	2.22
Around the Waist	3.89
Across One Shoulder	0.25

* $p < 0.0009$

Hip, knee, and ankle angles were similar during the baseline and the three load-carrying conditions. Subjects did not show significant differences in maximal heart rate. The mean maximal heart rate ranged from 130 beats/minute when carrying the load across one shoulder to 137 beats/minute when carrying the load on the back. Subjects did not showed any significant differences in the perceived rate of exertion. The perceived rate of exertion was the lowest when carrying the load around the waist (4.3 +/- 0.4) and the highest when carrying the load across one shoulder (5.9 +/- 0.9). Subjects did not show significant differences in the level of discomfort reported. The researchers found the discomfort reported by the subjects was the lowest (5 +/- 1 mm) when they carried the load around the waist and the highest (64 +/- 9 mm) when they carried the load across one shoulder. Subjects reported high levels of discomfort generally towards the end of the treadmill session.

The researchers conducted the multiple regression analysis in three steps to examine the influence of each shoulder muscle group on trunk and shoulder angle deviations at heel strike. Trunk angle deviation was the absolute difference between trunk angle during the baseline condition and during each load carrying condition. Shoulder angle deviation was calculated in a similar manner. The researchers first entered the horizontal abductors and horizontal adductors, then the abductors and the adductors, and lastly the shoulder flexors and extensors into the multiple regression formula. The researchers found that at heel strike, six shoulder muscle groups strongly predicted the trunk angle when subjects were carrying the load around the waist ($r^2 = 0.941$). Shoulder girdle muscle strength also positively correlated with trunk angle when subjects were carrying the load across one shoulder ($r^2 = 0.72$) and on the back ($r^2 = 0.65$) (see Table 5). The researchers found that at heel stroke, six shoulder muscle groups strongly correlated with the shoulder angle deviations when subjects carried the load on the back ($r^2 = 0.697$) and around the waist ($r^2 = 0.621$) (see Table 6).

Table 5. Multiple Regression Analyses (r^2) of Shoulder Girdle Muscle Strength and Trunk Angle Deviations at Heel Strike

	Backpack	Waist	Shoulder
Step 1	0.085	0.468	0.284
Step 2	0.11	0.885	0.612
Step 3	0.65	0.941	0.72

Step 1. Horizontal abductors and horizontal adductors
Step 2. Muscles from Step 1, abductors, and adductors
Step 3. Muscles from Step 2, flexors, and extensors

Table 6. Multiple Regression Analyses (r^2) of Shoulder Girdle Muscle Strength and Shoulder Angle Deviations at Heel Strike

	Backpack	Waist	Shoulder
Step 1	0.476	0.272	0.215
Step 2	0.593	0.371	0.263
Step 3	0.697	0.621	0.375

Step 1. Horizontal abductors and horizontal adductors
Step 2. Muscles from Step 1, abductors, and adductors
Step 3. Muscles from Step 2, flexors, and extensors

Discussion

An optimal load-carrying configuration should allow a person to walk with normal reciprocal shoulder, trunk, and leg movements with the least of amount of effort and discomfort. Subjects showed similar hip, knee, and ankle angles when walking with no load and carrying the load in three configurations. Subjects showed changes in trunk and shoulder angles. Carrying the load around the waist appeared to be the optimal load-carrying configuration according to the results of this study. Subjects showed similar trunk and shoulder movements during the baseline (no load) condition and when carrying the load around the waist. Subjects reported low levels of perceived rate of exertion and discomfort while carrying the load around the waist. Carrying the load on the back appeared to make subjects flex the trunk more forward with limited trunk forward/backward movements during ambulation. Our findings are supported by the findings of Harman and his associates (1999). Harman and his associates reported that female soldiers showed more trunk forward flexion when the load carried in a specialized frame increased. The least favorable load-carrying configuration tested in our study was carrying the load across one shoulder. Subjects showed significantly more shoulder asymmetry and significantly less shoulder movements when carrying the load across one shoulder. Subjects reported the highest level of discomfort when carrying the load across one shoulder. Subjects reported discomfort on neck, shoulder, and back when carried the load across one shoulder. They kept moving their shoulders trying to shift the load while walking on the treadmill. The task tested in this study was walking on a treadmill at 3.3 miles/hour with the gradient changing every ten minutes from one to seven percent. The physiological work performed by subjects on the treadmill appeared to be within their physical tolerance as indicated by similar heart rate between the baseline measurement and the three load configurations.

The researchers examined the influence of the shoulder girdle muscles on the deviation of the trunk and shoulder movements when carrying the load from the baseline condition. When carrying the load around the waist, the shoulder horizontal abductors, horizontal adductors, abductors, and adductors strongly influenced subjects' trunk movement deviations. The shoulder girdle muscles (horizontal abductors, horizontal adductors, abductors, adductors, flexors, and extensors) strongly influenced subjects' shoulder movement deviations when carrying the load on the back or around the waist. Apparently, shoulder girdle muscle strength positively correlated with a woman's trunk and shoulder movements while walking with a heavy load around the waist or on the back.

Conclusion

Carrying a heavy load around the waist appeared to be most optimal for women, causing the least deviation from normal gait pattern, least effort, and the lowest level of discomfort. Shoulder girdle muscle strength positively influences shoulder and trunk deviations during ambulation when women carrying a heavy load around the waist or on the back.

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Load Lugging Locomotion: Lessons from Indigenous People, Rhino Beetles, and Wallabies

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Summary

Two fundamental mechanisms underlie walking and running. Walking involves an inverted pendulum-like exchange of kinetic and gravitational potential energy. Running involves spring-like exchange between kinetic and gravitational potential energy with elastic energy stored in the tendons. People are better able to utilize the inverted pendulum mechanism when loads are carried on the head and this method allows small loads to be carried for free. However, there is not a clear link between the mechanical work performed in walking and the metabolic cost. Rhinoceros beetles are able to carry enormous loads very cheaply but how they do so is not clear. People can use external springs to carry loads more comfortably, but not more cheaply. But kangaroos and wallabies can use internal springs to save energy during their hopping gait and to carry loads in their pouches. These examples can inspire novel means of improved human load carriage.

Introduction

We can learn a great deal about the biomechanics and energetics of load carriage from indigenous people and animals in nature. Many indigenous people carry staggering loads and in some cases with remarkable economy of effort. Animals ranging from ants to wallabies carry loads cheaper than predicted by conventional theories. Studying this anthropological and zoological diversity has revealed mechanisms and movement patterns that can stimulate creative load carrying equipment designs and techniques. But, before I can introduce examples of these unique mechanisms of load carriage, it is important to explain the basic mechanisms of normal, unloaded walking.

Discussion

Walking fundamentally involves an inverted pendulum-like mechanism (Figure 1) that conserves mechanical energy (Cavagna et al. 1977). At the beginning of the stance phase of walking the center of mass of the body is low but the forward velocity of the center of mass is at its maximum. Thus, the gravitational potential energy (mgh) is at first relatively small while the kinetic energy ($1/2\ mv^2$) is great. As the body arcs up over the rigid support leg to its highest point, the body slows and the kinetic energy is converted into gravitational potential energy. During the second half of the stance phase, the body falls and velocity increases. The gravitational potential energy is converted back into kinetic energy during this second half. Thus, kinetic and gravitational potential energies are exchanged and the muscles need not do all of the work to lift and accelerate the center of mass during each step (W_{com}). The degree to which this energy exchange takes place has been quantified as a “per cent recovery”. Most humans appear to recover about 65% of the energy from step to step in walking and this presumably minimizes the metabolic cost of walking.

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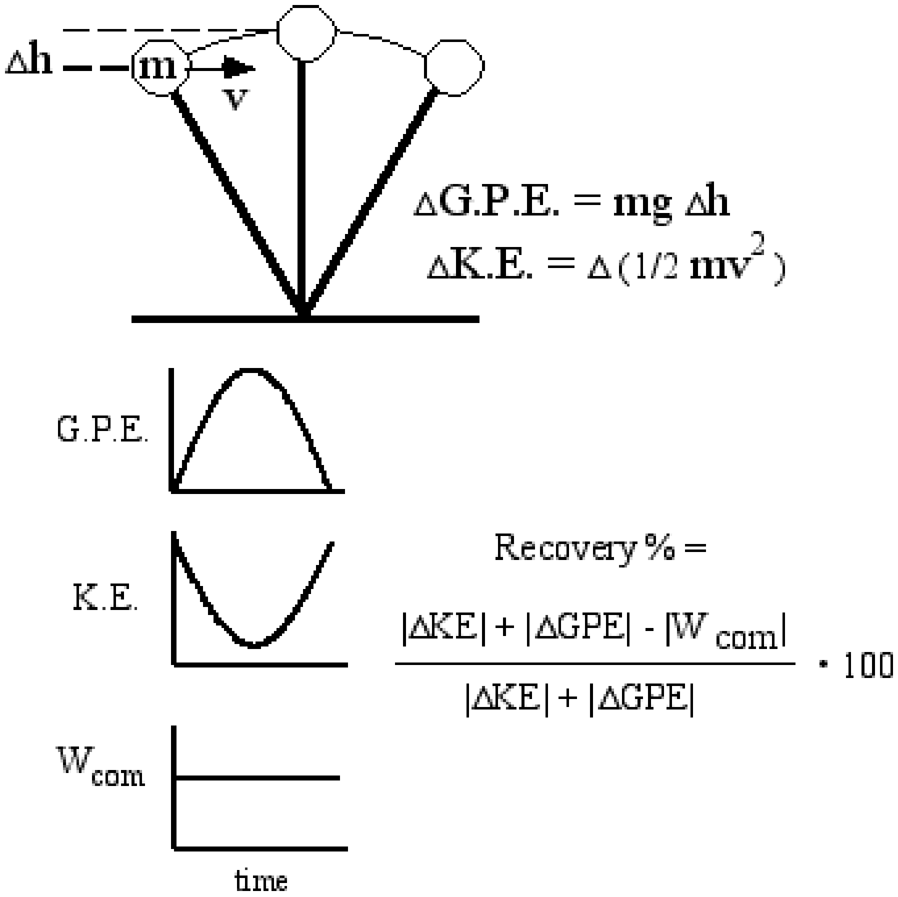

Figure 1. Walking, likened to an inverted pendulum-like mechanism

Inverted pendulum-like recovery of mechanical energy seems to be best perfected by people who carry loads perched on top of their head. This method of load carriage is common in many parts of the world but the techniques used by African women have been best studied. One advantage of head load carrying is that the load is directly in line with the body’s center of mass and thus no compensating torque must be exerted. Maloiy et al. (1986) were the first to show that head load carriage is remarkably economical. They found that experienced head load carriers could carry up to 20% of their body mass on their heads with no measurable increase in metabolic energy consumption! After some years of speculation about the mechanism, Heglund et al. (1995) demonstrated that trained head load carriers are able to recover a greater percentage (up to 75%) of the mechanical energy fluctuations within a step and thus reduce the work input required. This certainly could explain part of their remarkable energetics.

However, recent research in my laboratory indicates that the link between mechanical work performed and metabolic cost of walking is more complicated. Instead of head loads, we studied loads carried symmetrically about the waist. To accomplish this, we wrapped lead strips over a padded hip belt. With this method, the center of mass of the load is also directly in line with the body’s center of mass and thus no compensating torques need to be exerted.

We found that moderate symmetric waist loads are not carried for free; the metabolic cost increased directly with the load carried up to 20% of body mass. Like head load carriage, with heavier symmetric waist loads the per cent recovery of mechanical energy increased. Also similarly, the mechanical work performed on the center of mass + load did not increase for loads greater than 20% of body mass. Yet, unlike the head load carriers, the metabolic energy consumed by the symmetric waist load carriers increased dramatically for heavier loads. Thus, we saw a disconnection between the metabolic cost of locomotion and the external mechanical work performed.

It appears that the metabolic cost of walking is determined by three factors: the cost of performing external work, the cost of generating muscular force to support body weight and the cost of swinging the limbs. But what is the relative cost of these three components?

To try and distinguish the cost of performing external work and the cost of generating force, we studied “negative load carriage”. That is, we examined the mechanics and energetics walking in simulated reduced gravity (Griffin et al., 1999). To simulate reduced gravity, we pulled up on the subjects via a waist-torso harness attached to stretched elastic rubber tubing (Figure 2).

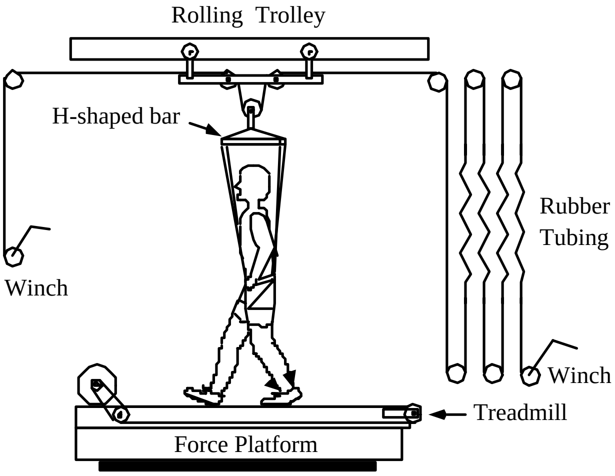

Figure 2. Experimental set-up for simulating reduced gravity

If the cost of generating force is the primary determinant, one might guess that in 50% of Earth gravity, metabolic cost would be 50% of normal. However, Farley & McMahon (1992) showed that the effect of reduced gravity is more modest. We investigated if low gravity walking was not as cheap as expected because of a disabling of the inverted-pendulum mechanism. That was not the case. Subjects adjusted their gait so as to reduce their kinetic energy fluctuations and thus match the reduced gravitational potential energy fluctuations. In other words, they walked with a more constant velocity and they had similar per cent recovery values. As a result, the calculated mechanical work performed decreased directly with the reduced gravity.

Thus, reduced gravity walking is another situation where metabolic cost does not parallel the mechanical work performed. Yet, metabolic cost did not exactly parallel the cost of generating force either.

As impressive as human feats of strength and load carrying can be, they are dwarfed by the abilities of other species. Every child knows that ants can carry many times their own body weight. In natural situations they “only” carry about 2 or 3 times their own body weight on a regular basis (Lighton et al., 1993). The maximum load that ants can carry is about 10 times body weight. The alleged world record holders for load carrying are rhinoceros beetles. The Guinness Book of World Records purports that rhino beetles can carry 850x their own body weight (Matthews, 1992). After reading that, I became very curious to find out if it was true or even possible. I obtained some beetles from Arizona and immediately began my investigation.

So, how much weight can a rhinoceros beetle carry? Unlike ants, beetles do not naturally carry loads but it is easy to attach weights to their exoskeleton using glue and Velcro. I found that these beetles could walk or perhaps more accurately, stagger with up to 80 times their own weight. With greater weights, the beetles were not hurt, but refused to walk. With loads up to a still impressive 30 times their own weight the beetles readily marched along. We know that in humans and other animals, the metabolic rate typically increases in direct or greater proportion to the load being carried (Taylor et al. 1980). If that rule held true for beetles, they would need to have an enormous aerobic capacity to carry 30 times their own weight.

To investigate the energetics of rhinoceros beetle load carriage I walked them with various loads in a treadmill-respirometer chamber (Figure 3) and measured their rates of oxygen consumption (Kram, 1996).

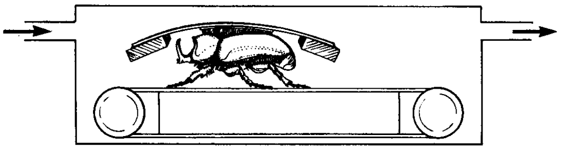

Figure 3. Measuring oxygen consumption of rhinoceros beetles carrying loads

Rather than finding that beetles have enormous aerobic capacities, I found that they instead carry loads with remarkable economy. When walking with a load of 30 times body weight, they increased their metabolic rate to only about 4 times their normal unloaded walking cost! That is, carrying a gram of load was about eight times cheaper than carrying a gram of body mass.

Unfortunately, I have not yet been able to definitively explain this phenomenon. The beetles do not appear to be sliding their abdomens on the ground when they walk with these loads. It may be that they are able to support the weight using non-metabolizing exoskeleton structures. Another possibility is that their muscles are unusually efficient, but this species is not unusually efficient when walking without loads. It seems unlikely that these beetles use the same trick as the African women head-load carriers. The beetles move too slowly for there to be useful exchange of mechanical energies. For now, this mystery remains unsolved. But just imagine if a human could transport 30 times their own weight (~4500 lbs.) with less effort than it takes to jog.

Turning now to running gaits, it is again important to review the fundamental mechanism underlying normal unloaded gait. In contrast to the inverted pendulum of walking, in running the legs do not act like rigid struts but rather like bouncing springs (Farley & Ferris, 1999). At the beginning of the stance phase of running the center of mass of the body is still relatively high and the forward velocity of the center of mass is at its maximum. Thus, the gravitational potential energy (mgh) and the kinetic energy ($1/2\ mv^2$) are both great. During the stance phase, the body slows, the leg flexes and the center of mass reaches its lowest point. Accordingly, the gravitational potential energy and kinetic energy reach minimum values at the middle of the stance phase. However, during the first half of stance, both forms of energy are stored as elastic spring energy primarily in the tendons of the leg extensor muscles. During the second half of the stance phase of running, the tendons recoil and the elastic energy is converted back into gravitational and kinetic energy.

Tendons can return as much as 93% of the energy stored in them (Alexander, 1988). Thus, the muscles need not repeatedly perform work to lift and accelerate the center of mass during each step. This dramatically reduces the metabolic cost of running.

Taylor et al. (1980) showed that for a variety of running animals the cost of carrying a load was directly proportional to the load expressed as a percent of the body mass (see Figure 4). These and other experiments led to the idea that the metabolic cost of running is determined not by the mechanical work done but by the magnitude and rate of force generation (Kram & Taylor, 1990). In short, the idea is that during running the muscles act primarily as nearly isometric force generators that allow the tendons to function like springs.

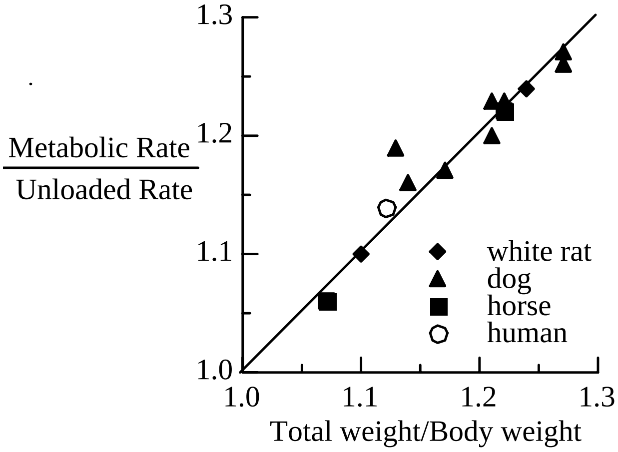

Figure 4. Metabolic cost of load carriage for a variety of running animals (from Taylor et al, 1980)

Hopping marsupials (e.g. wallabies and kangaroos) provide the most intriguing evidence for the importance of springs in locomotion and load carrying. In one of the most dramatic discoveries in the study of locomotion, Dawson and Taylor (1973) discovered that unlike all other species, as red kangaroos hop at progressively faster speeds they consume metabolic energy at the same rate! Even hopping at a 4-minute mile pace, kangaroos are only at about a third of their aerobic capacity (Kram & Dawson, 1998). This phenomenon is also difficult to explain. As kangaroos hop faster they must generate muscular force more rapidly which is generally more expensive. However, it may be that the muscles and tendons of kangaroos are “tuned” to function best at faster hopping speeds. At least one aspect of kangaroo locomotion energetics seems normal: they do consume energy more rapidly when they hop uphill (Kram & Dawson, 1998).

Besides their distinctive bouncy hopping mode of locomotion, the best popularly known feature of kangaroos is the female’s pouch. Young kangaroos (joeys) are carried in the pouch while the mother hops about her business. Baudinette and Biewener (1998) investigated the metabolic cost of carrying weight in the pouch by Tammar wallabies, which are smaller relatives of red kangaroos. They studied female adults hopping on a treadmill while carrying 15% of their body mass in their pouch. Just as Dawson and Taylor found for speed, Baudinette and Biewener found that pouch loads were carried without any additional metabolic cost! This is difficult to explain, but again a tuning argument for musculoskeletal springs seems most plausible.

Running humans can not only tune the spring-like properties of their legs (Ferris et al., 1999) but we can also tune the external springs used to carry loads. People throughout Asia carry loads using springy bamboo or wooden poles slung over the shoulder (Figure 5).

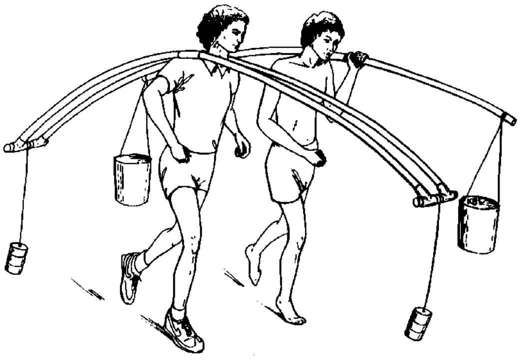

Figure 5. The carriage of loads using springy bamboo or wooden poles

These poles are distinctly different from the rigid yokes used by oxen. The yoke for oxen is designed to be rigid so as to maximize the transmission of force from the animal to the implement. For human load carriage, the goal is the opposite. To maximize comfort, the pole should act as a suspension system that reduces the peak forces experienced by the shoulder. Thus, a springy pole used by a human to carry loads is ideally very compliant, with a low natural frequency of vibration. The natural frequency of vibration for a spring-mass system is equal to the square root of k/m where k is the spring stiffness and m is the mass supported by the spring. A springy carrying pole should have a natural frequency of less than one third of the excitation or driving frequency. When a person jogs, they have a step frequency of about 3Hz. That is, their shoulder oscillates vertically (driving the vibration of the spring-mass system) about 3 times per second. Thus, according to engineering theory, a springy carrying pole should have a natural frequency of less than 1Hz.

My empirical measurements of the biomechanics of pole carrying bear out this theory (Kram, 1991). When a person jogs, the peak vertical ground reaction force is about 2.5 times their own body weight. Thus, if a load is rigidly attached to the body, it would slam on the shoulders with ~2.5 times its weight with every step. However, with a properly tuned carrying pole, I found that the force exerted by the load on the shoulder was quite steady and moderate. The force fluctuations were less than 10% of those expected with a rigidly attached load.

Of course, I was also curious to see if a springy pole allows loads to be carried cheaply, akin to the kangaroo and wallaby findings. Unfortunately, I found no energetic savings during springy pole load carrying. The cost of carrying loads was the same as with a normal backpack. However, carrying poles do offer other biomechanical advantages in addition to the peak load reductions. Because the loads are carried symmetrically front to back, they reduce the need to exert torques about the hips to lean forward. Because the loads are suspended from the poles by strings or ropes, the loads are carried with a low center of gravity and thus may be more stable. Finally, poles allow heavy loads to be hoisted by an individual without assistance. The person can crouch down under the pole, slackening the ropes, then stand up straight, and thus don the load without lifting it high in the air. Springy poles used for load carriage are a remarkably simple example of “appropriate technology” that has many ergonomic benefits. Perhaps they can inspire designers to incorporate compliant suspension systems into load carrying systems used by soldiers.

Conclusions

To sum up, elucidating the biomechanical bases for the metabolic costs of walking and running remains a major challenge for biomechanists and physiologists to solve together. In addition to the basic science questions, if we can unravel this enigma it will aid in the optimization of load carrying techniques and equipment. That would be only fair, since practical studies of load carrying have clearly provided insights into normal unloaded locomotion biomechanics and physiology. Studying the load carriage practices of indigenous people and of animals in nature has and will continue to breathe fresh ideas into these fields of inquiry.

Acknowledgments: Supported by NIH grant AR 44688.

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Development of a Suite of Objective Biomechanical Measurement Tools for Personal Load Carriage System Assessment

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Summary

The proper design of personal load carriage systems may be critical not only for soldier comfort, but also for soldier mobility and performance on the battlefield. Evaluation of soldier personal load carriage systems typically involves the conduct of human-based lab and field trials that can be both time-consuming and costly to conduct. Field testing usually requires multiple system prototypes of a given design iteration, with their development cost often limiting the number of design iterations tested. Human-based trials also rely on subjective opinion for system assessment. While the opinions of the ultimate users have face validity, and bias and error can be controlled in such trials, it is also desirable to have objective load carriage assessment methods and analysis tools that permit rapid analysis, design iteration and evaluation. Canada has developed biomechanical assessment and analytical tools to supplement human-based load carriage system assessment methods. This suite of tools permits efficient objective evaluation of important biomechanical aspects of load-bearing webbing, vests, packs and their components, thus contributing to early system assessment and a rapid iterative design process. This paper will introduce each of the assessment and analytical tools, their rationale, the objective measures available and the recommended performance criteria for acceptable military load carriage systems. Separate papers in these proceedings will provide the details of validation and utility of the tools that have been developed by Canada.

Introduction

Over the past several years, Canada has undertaken a research and development programme to investigate and understand the factors affecting human load carriage performance and apply that knowledge to the development of advanced load carriage systems for the soldier of the future. This research and development has been conducted by the Defence and Civil Institute of Environmental Medicine (DCIEM) through a series of contracts to the Ergonomics Research Group of Queen's University.

As this R&D programme was being launched, it became apparent that there were few tools available for the objective comparative evaluation of load carriage systems and their design features. Therefore, the aims of the research programme were fine-tuned to include the following:

- To provide a scientific basis upon which load carriage systems could be selected or designed;
- To develop and apply standardized testing methods to quantitatively evaluate load carriage system designs; and
- To optimize load carriage capacity for the soldier (not necessarily to enable them to carry more, but to allow them to carry loads more efficiently with improved performance, comfort and safety).

Paper presented at the RTO HFM Specialists' Meeting on "Soldier Mobility: Innovations in Load Carriage System Design and Evaluation", held in Kingston, Canada, 27-29 June 2000, and published in RTO MP-056.

Research Programme Methodology

The approach that was taken to help achieve the foregoing research aims involved the following: a thorough state-of-the-art and literature review (Pelot et al, 1995) (including identification of threshold limit values based on survival, injury and tissue tolerance data as well as a review of existing measurement methodologies); identification of those measures relevant to human comfort, tissue tolerances, and load carriage capability; investigation of methodologies suitable for the evaluation and differentiation of load carriage system and component designs; development of a suite of objective biomechanical load carriage assessment tools to augment traditional evaluation methods (Stevenson et al, 1995); validation of these tools through testing of a range of commercial and military load carriage designs using a range of measurement methodologies (Stevenson et al, 1996 & 1997c); and application of these methodologies and findings to develop recommended load carriage system performance criteria, a static biomechanical load carriage model (Stevenson et al, 1995; Pelot et al, 1998a), and a new load carriage system for the Canadian Forces (Bryant et al, 1997a, 1997b & 1997c; Reid et al, 1998, 1999a, 1999b & 1999c; Stevenson et al, 1998).

This report will provide an introduction and overview of the objective biomechanical measurement tools developed and used by Canada for load carriage system evaluation. Several other papers in these proceedings describe the validation and accuracy of these measures (Bryant et al, 2000; Morin et al, 2000), the development of performance-based load carriage system ranking criteria (Bryant et al, 2000), the development of a static model of load carriage (Pelot et al, 2000), and the use of these tools in the iterative development and evaluation of a new load carriage system for the Canadian Forces (Bossi & Tack, 2000; Reid et al, 2000a & 2000b; Stevenson et al, 2000).

Rationale for Novel Measurement and Analysis Tools

A review of scientific and technical literature (Pelot et al, 1995; Stevenson et al, 1995 & 1996) identified a range of factors known to affect human load carriage as well as a number of load carriage system evaluation methods. These methods included psycho-physical (e.g., ratings of perceived exertion, local discomfort ratings), physiological (e.g., metabolic energy cost, cardiorespiratory and other indicators of body strain), biomechanical (e.g., EMG, film analyses of posture and gait patterns, force platform measures of ground reaction forces, skin pressure) and mobility performance measures. Virtually all evaluation methods relied on human subjects carrying loads of various configuration (weight, load location, load carriage device) while performing relevant tasks (such as marching or obstacle clearance) with varying duration, distance, terrain condition and/or speed.

The psycho-physical, physiological and biomechanics measures used have been instrumental in understanding the many factors affecting human load carriage performance (i.e., load, load placement, environmental conditions, physical fitness, terrain conditions, and many other factors as reviewed by the keynote speaker at this Specialist Meeting [Knapik, 2000]). A number of measures have been sensitive enough to detect changes in load and load placement. But few, especially when considered in isolation, were considered by the authors to be effective for objectively discerning some of the more subtle design differences one finds between competing load carriage systems or between design iterations of a given system or feature.

To be of utmost value in the load carriage system design and evaluation process, the ideal measurement technique would have the following characteristics: be objective, reliable, and sensitive to subtle design differences; be related to human tolerance limits (for injury as well as discomfort, usability, and acceptability); and be applicable, easy and efficient to employ across a range of load carriage system/component designs. It is perhaps because there is no ideal single measure or approach that most assessments of load carriage systems/components have used a combination of various psycho-physical, physiological, biomechanical and task performance methods.

Psycho-physical and subjective methods are indeed valuable for gaining insights into energy expenditure, discomfort, and feature/functionality preferences. However, they may lack sufficient sensitivity to slight design differences in suspension systems, except for perhaps the most experienced backpackers (Pelot et al, 1995).

Physiological measures can differentiate loads (Epstein et al, 1987 & 1988; Morrissey, 1988; Pierrynowski, 1981) and gross load location (Balogun et al, 1986; Haisman, 1988; Legg, 1985; Legg & Mahanty, 1985 and many other references cited by authors of papers in these proceedings), but do not appear to offer the solution for differentiating some of the more subtle design differences one finds between competing load carriage systems or between design iterations of a given system (Kirk & Schneider, 1992).

Of all the measures reviewed, biomechanics measures appeared to offer the most promise for use in an iterative design process. A measure such as skin pressure (underlying pack shoulder straps for example) has been used to differentiate pack suspension systems (Holewijn, 1990; Holewijn & Lotens, 1992; Holewijn & Meeuwsen, 2000), and is related to subjective reports of discomfort as well as tissue tolerances (Goodson & Johnson, 1981; Goslin & Rocke, 1986; Holloway et al, 1976; Husain, 1953; Sangeorzan et al, 1989). Other biomechanical factors, such as forces and moments acting on the spine (determined traditionally through gait analyses), relative distribution of load between shoulders and hips, and relative motion between payload and body (Hinrichs et al, 1982) may also be important in the objective differentiation of load carriage system designs.

Because there exist few if any physical models of human load carriage, virtually all load carriage research has been based upon experimentation using human subjects. While this is ideal for face and content validity, it may pose problems relating to reliability and logistics. Human variability demands that a range of subjects be used for testing load carriage systems. This can be time-consuming to arrange and costly to conduct, especially considering the tremendous range of design options and iterations that could be assessed. Additionally, some important measures cannot be easily measured directly (i.e., forces and moments on the spine) although these are very important in the assessment of load carriage system safety/injury potential. Finally, user opinion (properly collected to control for bias) is invaluable for assessing the utility and usability associated with specific design features and localized comfort; however, reliance on subjective comfort ratings alone for the assessment of load carriage systems would be imprudent. The development of standardized and efficient objective biomechanical test and analysis methods is therefore considered important, in order to overcome some of the limitations cited. Not only would they provide quantitative data upon which design decisions could be made, but they would also serve to shorten the design iteration and evaluation cycle and delimit the number of design options that need be subjected to more costly time-consuming human/user-based evaluation.

In summary, the literature review conducted early in the research and development programme (Pelot et al, 1995; Stevenson et al, 1995) led to the principal conclusions that biomechanics measures, together with subject perceptions, would be good indicators of design variations in the load carriage system. And because the relationship between user perceived stress under load and quantitative measurements was not very well developed there was seen to be a requirement to develop a quantifiable, repeatable measure of the ergonomic merit of a load carriage design. For these reasons, the Canadian research and development effort was directed toward the development and validation of a suite of novel biomechanical assessment and analysis tools.

Novel Biomechanical Measurement Tools

The following tools have been developed and validated (Bryant et al, 1999 & 2000; Doan et al, 1998; Morin et al, 1998 & 2000; Reid et al, 1997; Stevenson et al, 1995, 1996, 1997a, 1997b, 1997c & 1998b) in order to facilitate the objective and efficient measurement of load carriage systems. Load carriage systems and their specific components can be evaluated within only a matter of days using these tools, making them invaluable in an effective iterative design and evaluation process.

Dynamic Load Carriage Simulator

General Description. The Dynamic Load Carriage Simulator shown in Figure 1 comprises a computer-controlled pneumatic system that moves with three degrees of freedom and displaces an instrumented anthropomorphic torso through a range of vertical motion representative of human gait. It is capable of simulating a range of gaits from normal walking, running, through to routines that simulate slipping on a surface or ducking under an overhead obstacle. Vertical displacement, rotation about the anterior/posterior axis (side lean), and rotation about the medial/lateral axis (forward lean) are user programmable from a menu.

The anthropomorphic torsos built for the Dynamic Load Carriage simulator comprise a fiberglass shell and internal structure with distributed body mass that is representative of humans. Four torsos have been built to represent the 95th and 50th percentile male, and 50th and 5th percentile female (for weight, critical girth, height and breadth measurements). Body weights range from 5th percentile female (470 N) to 95th percentile male (960 N). Anthropomorphic values are based upon the US Army survey of 1988 (Gordon et al, 1989). A range of skin analogues were evaluated and Bocklite® was chosen for its force/displacement and creep properties (very reproducible and less creep than other options evaluated).

Figure 1. Dynamic Load Carriage Simulator (can be programmed to walk, jog or run and is set-up to test a load-bearing vest design)

Outcome Measures. The outcome measures provided by the Dynamic Load Carriage Simulator include the following:

- Relative motion between payload and body in all three planes
- Forces and Moments acting upon the body in all three planes
- Skin contact pressures (both peak and average pressures)

Relative motion between payload and the body is important from a load control perspective. Payload refers not only to the load carried within a backpack, but also the contents individual pockets in a load-bearing garment. Ideally, the payload and body should move in unison in order to support stability and mobility, to minimize energy expenditure (Hinrichs et al, 1982), to avoid the potential for local tissue damage and to minimize any distraction that may be associated with the repetitive striking of payload against the body. The better load carriage system minimizes any differences in relative motion in all three axes. The Dynamic Load Carriage Simulator measures relative motion between payload and the mannequin in all three axes using the Fastrak® displacement measurement system during dynamic testing. The Fastrak® system involves a sensor (affixed to the payload of interest) which reports its displacement and orientation within a magnetic field. Outcome measures are relative motions in the X, Y and Z planes. System accuracy (RMS static = 0.66 mm, RMS dynamic = 0.65 mm) has been confirmed with the highly accurate Optotrak® system (Stevenson et al, 1996).

The measurement of forces and moments acting on the body is also critical for assessing load carriage system safety and injury prevention. There exist threshold limit values for forces to the spine at which injury can occur in all three axes (Goel et al, 1995; Waters & Rutz-Anderson, 1993). The dynamic load carriage simulator permits direct objective measurement of these forces and moments via the six degree-of-freedom load cell positioned at the height of hip joint rotation.

Skin contact pressures have been used to discern load carriage suspension system designs (Holewijn, 1990; Holewijn & Lotens, 1992; Holewijn & Meeuwsen, 2000) and are related to tissue tolerances. The contact pressures resulting from the carriage of heavy loads in poorly designed load carriage systems can result in discomfort, occlusion of blood vessels, pinching of nerves and even nerve damage (Goodson & Johnson, 1981; Holloway et al, 1976; Husain, 1953; Sangeorzan et al, 1989). The Dynamic Load Carriage Simulator permits measurement of average and peak contact pressures, and the identification of contact areas, hot spots and their sources. Average and peak skin pressures can be measured in those areas subject to contact with load carriage systems (typically shoulder, waist/hip and lumbar regions). Skin pressures are measured using the Tekscan F-Scan® pressure measurement system, shown at Figure 2, during dynamic or static testing. Average pressure refers to the average pressure across those cells triggered in a specific body region (such as anterior or posterior shoulder). Peak pressure is the highest pressure recorded for a given pressure sensel. Figure 3 shows the typical output displayed for an in-service military pack. The arrows indicate how even simple strap surface features can contribute to underlying skin contact pressures (which in this case exceeded recommended limits).

A number of tests have been performed to examine F-Scan® reproducibility, the effects of temperature, sensel usage rates and error due to sensor curvature (Morin et al, 1998; Stevenson et al, 1995). Standard errors are as follows: 9.6% of the mean for average pressure during dynamic testing; 14% of the mean for peak pressure during dynamic testing; and 9% of the mean for error due to sensor curvature. Although some studies have been conducted (Bryant et al, 1999; Morin et al, 2000; Wilson et al, 2000), research is ongoing to create calibration curves for individual sensels, to improve the accuracy of the F-Scan® system and its ability to discriminate between load carriage systems and/or components in this as well as *in-situ* applications.

Figure 2. Typical Placement of F-Scan Contact Pressure Measurement System

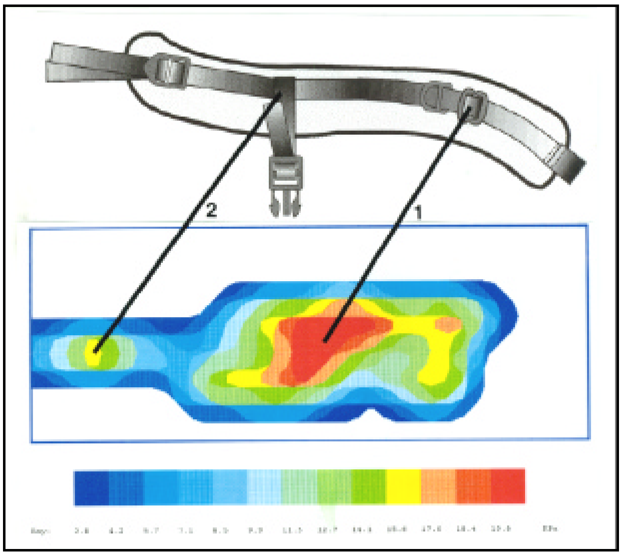

Figure 3. Typical F-Scan Output for an in-service military pack shoulder strap

Input Variables. The input variables during Dynamic Load Carriage simulator testing set-up include gait parameters (style and speed), body lean angles and pack suspension system strap tensions. The programmable simulator can be adjusted to provide pure sinusoidal motion or variations more closely approximating human gait. Speeds can also be adjusted up to 3 Hz or 5.6 km/hr.

A six degree-of-freedom load cell is positioned in the Dynamic Load Carriage Simulator at the height of hip joint rotation. The body-fixed system measures hip reaction forces and forward lean is adjusted prior to testing so as to balance the hip moment.

Custom strap force transducers were produced so that strap tension could be used as a standardized input across load carriage systems. Strap tensions are based upon realistic tensions set by experienced pack users. Tension can be set for shoulder straps, load lifters, shoulder and hip stabilizer straps, hip belts or any other straps included in a given load carriage system design. The custom strap force transducers shown in Figure 4 comprise a link with two strain gauges mounted to measure axial force. The strap force transducers are highly accurate (+/- 2 %) and linear ($R^2<0.9995$) (Reid et al, 1997); however, straps must be modified sometimes to accommodate these devices. An *in-situ* strap force measurement device that does not require permanent fixation to the strap has been developed and is undergoing evaluation for accuracy and reliability.

Figure 4. Custom strap force transducers for measuring strap tension.

Range of Motion (ROM) Stiffness Tester

Rationale. Restriction of the rotation of the trunk during normal gait has been shown to cause an increased energy cost (Inman et al, 1994). Furthermore, the ability to lean over is often necessary in military load carriage, for stealth, in order to avoid overhead obstructions or for crossing obstacles. Stevenson et al. (1997a) provided evidence that pack stiffness was related to soldier opinion of mobility, manoeuvrability and comfort during marching and mobility tasks. Motion restrictions in any axis may contribute to user fatigue and poor mobility performance. A Range of Motion Stiffness tester was therefore developed in order to develop objective measures of the restriction of motion caused by a load carriage system.

Description. The ROM stiffness tester is shown at Figure 5. It permits the simulation of the human motions of forward flexion, upper trunk rotation and sideways bending and the measurement of static or dynamic stiffness of a pack. The tester comprises a 50th percentile male torso (similar to that used in the dynamic load carriage simulator) that incorporates a thrust bearing (which allows trunk rotation) and a clevis hinge (permitting forward and sideways lean) at the level of hip flexion.

Outcome Measures. Once a load carriage system is fitted to the torso (using standardized representative strap tensions, as for the dynamic simulator), it is exposed to a range of rotation/bending adjustments. Motion is created by a computer-controlled motor about either the flexion/extension axis, the torsional axis or in lateral bending. Outcome measures include flexion stiffness (N/deg), torsional stiffness (N/deg), forwards and sideways bending resistance (N/deg) and break angles (deg). The angular displacement is measured by a multi-turn potentiometer and the resistance to motion is measured by strategically positioned strain gauges.

Figure 5. Range of Motion Stiffness Tester

Static Load Distribution Mannequin

A Static Load Distribution Mannequin (see Figure 6) was developed to facilitate standardized static objective biomechanical testing. The static tester is similar to the Dynamic Load Carriage Simulator except that its base is designed to sit on a 6 degree-of-freedom force platform and an additional load cell was introduced between the upper torso and hips, permitting the assessment of relative load distribution between the shoulders and hips.

The relative distribution of load between shoulders and hips is an important measure. The ability to transfer load off the shoulders onto the hips is a desirable characteristic of a backpack. Not only does this bring the load closer to the body’s centre of mass, but the hips are also considered to be able to tolerate pressures more readily than the shoulders (Scribano et al, 1970, as cited in Holewijn & Meeuwsen, 2000)

The Load Distribution Mannequin has been used for answering specific pack feature design questions, such as optimal pack shoulder strap configuration (Whiteside et al, 1999), utility of lateral suspension rods in packs (Reid et al., 1999c; 2000a), and optimal attachment of the shoulder straps to the base of the pack (Reid et al, 1998; 2000b; Reid & Whiteside, 2000b). Load distribution (between shoulders and hips) has been assessed for a range of suspension system features and settings. The mannequin has also been used to develop and validate a static mathematical model of backpack load carriage (Pelot et al 1998a & 1998b) which is introduced below and described in detail in a separate paper in these proceedings (Pelot et al, 2000).

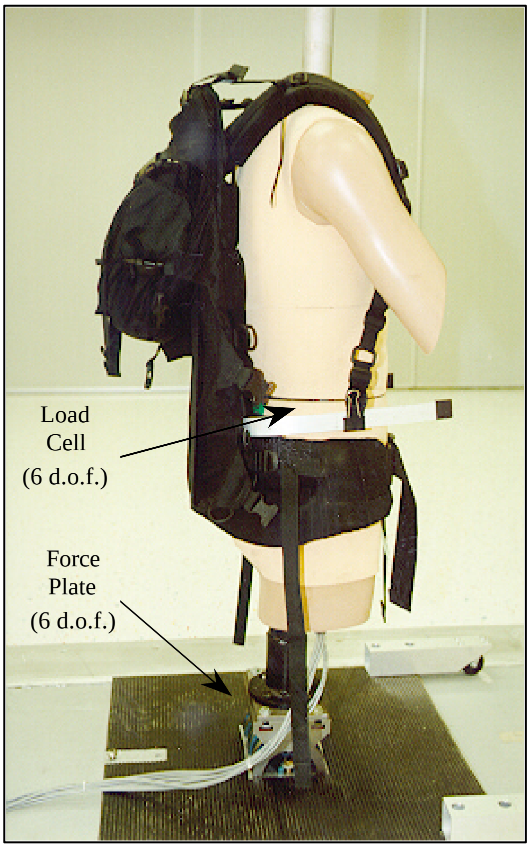

Figure 6. Load Distribution Mannequin (set-up for a study that examined shoulder strap attachment location/angle and its effect on load distribution between shoulders and hips)

Static Biomechanical Model and Analysis Tool

The static Load Distribution Mannequin was used to develop static biomechanical models of pack systems. Input values are shown at Figure 7a and include strap locations, strap angles, strap tensions, lean angle and pack weight. Model outcomes, also at Figure 7b, include the major body reaction forces associated with comfort scores on testing with human subjects, shoulder reaction forces and low back contact force. The model is based upon a simple pack with shoulder straps and hip belt. Further work is ongoing to model the impact of more advanced pack features such as load lifters, shoulder and hip stabilizer straps, lateral suspension stiffness rods, etc. Work is also underway to develop dynamic models for the future.

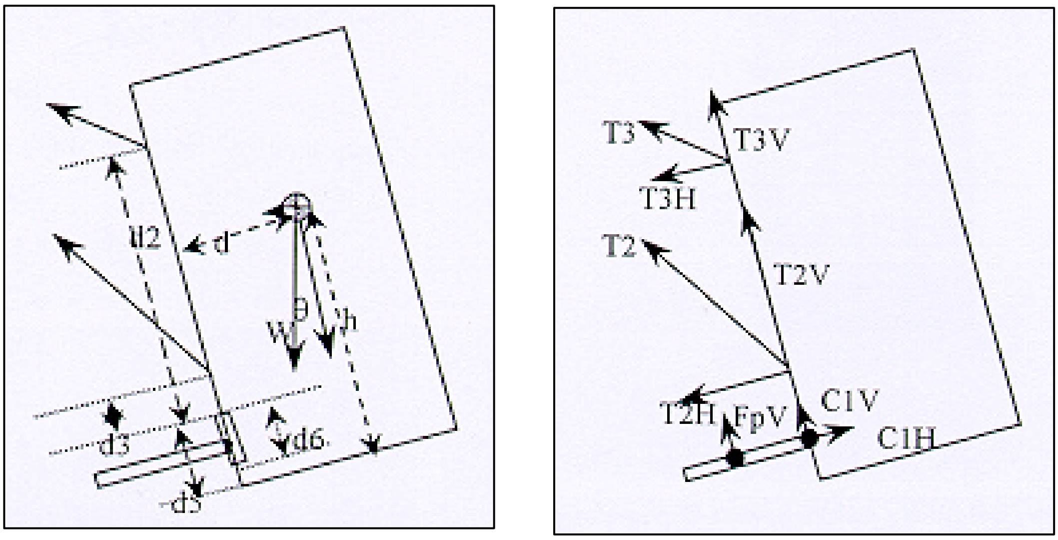

Figure 7. Static biomechanical pack model indicating input values (a-left) and outcome values (b-right)

Mobility Circuit

Despite the development of the foregoing objective measurement and analysis tools, the authors cannot stress enough how important human/user input is to the design and evaluation process. As mentioned previously, the suite of tools provides an efficient method for obtaining scientific performance data on the biomechanical properties of a given load carriage configuration. However, there are many aspects of a load carriage system that cannot be adequately addressed by biomechanics alone (especially those relating to comfort, functionality, usability). The comprehensive load carriage design and evaluation process used by Canada, therefore, included user focus groups and surveys as well as lab and field-based user trials throughout the iterative design process.

A mobility circuit has been designed and used to help validate the measures obtained from the foregoing biomechanical assessment tools. The mobility circuit presents a standardized set of tasks and movements that are representative of those that could be experienced by load carriage system users in field conditions and that permit user-based evaluations of load control and comfort. The circuit comprises a set of test stands including the following: bent and straight balance beams; boulder hop; fence climb; agility run; side slope walk; forward ramp climb; range of motion assessments; mouse hole clearance; and a range of relevant static tasks (i.e., emergency doffing, access to critical kit items, adoption of firing positions, etc). These are described in more detail in a separate paper in these proceedings (Bryant et al, 2000).

As part of the development and validation of the objective biomechanical tools and methods, and in order to be able to recommend performance-based biomechanical criteria for pack selection, a study was conducted to compare the physical measures from the new suite of tools with measures of human mobility performance and acceptability obtained during human trials across a range of load carriage systems. Results indicate strong correlation between a number of measures (Bryant et al, 2000; Stevenson et al, 1996; 1997a & 1997c) and support the validity of the objective measurement tools.

Portable In-situ Measurement System

Users vary tremendously in size, shape and preference for pack fit and adjustment, and these variances are represented to only a limited degree in the aforementioned suite of tools. Therefore, there is a desire to obtain objective measures *in-situ*, while real soldiers wear the load carriage system in question under realistic conditions. One would expect that the number of variables and strength of correlation between psycho-physical, subjective, physiological and biomechanical measures could be even higher than those established if it were possible to collect all data at the same time.

Canada is now developing an objective measurement system that can be worn by pack users during representative field tasks and permit simultaneous recording of a range of measures similar to those collected using the tool suite as well as other measures indicative of soldier performance, strain and/or comfort. The system will be used to collect data for the following purposes: to determine the most critical variables affecting load carriage performance, to further develop and validate the suite of objective biomechanics measurement and analysis tools, to assist with development of a dynamic biomechanical model, and to advance the state of knowledge regarding pack-wearer interaction.

Recommended Performance Specifications

Table 1 shows those performance-based specifications that are recommended by the literature reviewed and research conducted over the past several years. These are based upon the results of evaluations of a number of different load carriage systems (commercial and military), using a range of test methodologies (objective biomechanical tools, human mobility circuit trials), as well as injury and tissue tolerance data from the scientific literature that has been reviewed.

Table 1. Recommended performance specifications for military backpacks

Criterion	Recommended Value
Relative motion between pack and person	< 14 mm
Average skin contact pressure	< 20 kPa
Maximum continuous skin point pressure	< 45 kPa
Forces borne by the shoulders	< 290 N
Lumbar shear contact force	< 135 N

Load Carriage System Design Approach

It is suggested that the development of physical and mathematical models of load carriage will increase understanding of the factors contributing to soldier load carriage performance and also contribute to a more efficient, perhaps less costly, iterative development cycle.

Figure 8 depicts where physical and mathematical models of human load carriage might be inserted into the design process. By no means do these models intend to replace human-based testing or the requirement for interaction with end users (i.e., via focus groups, laboratory and field trials). A user-centered approach, which involves users throughout the design and evaluation process, is still strongly advocated.

Physical and mathematical models/tools can augment traditional human-based evaluation methods and permit efficient design iteration and evaluation without the need, at each design iteration, to conduct time-consuming and sometimes costly human-based trials. The suite of tools, as described in this paper, offer the ability to obtain objective performance data for a given load carriage system design, within only a matter of days of producing a prototype or design concept.

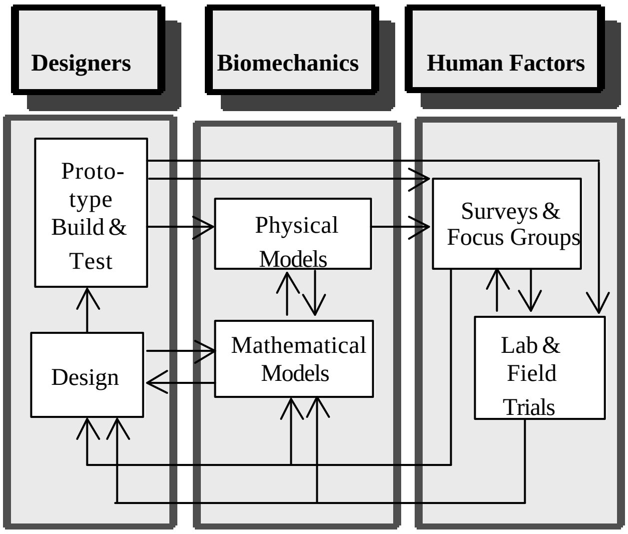

Figure 8. Canadian Load Carriage System Design Approach

With properly validated mathematical models and analysis tools, it may not even be necessary to build prototypes in order to answer some design-specific questions. If more design iterations are permitted (whether real or virtual) and objective performance data are available for system components and the system overall, one could reasonably expect that any load carriage system that is developed using these models should be much improved over those developed in the traditional manner.

This rationale and design approach was used in the development of a new load carriage system for Canadian Forces soldiers (under the Clothe the Soldier acquisition programme). The physical and mathematical models that were developed by Canada in its research programme proved to be invaluable in the design and rapid objective evaluation of a range of components comprising the new rucksack suspension system and its integration with underlying clothing and equipment layers. User focus groups and trials confirmed improvements in suspension system design and were also invaluable in the assessment and determination of pack form and function beyond those relating to biomechanics (e.g., usability, thermal characteristics, bag and modular pouch design, closure mechanisms, compatibility, soldier task performance, etc.).

The suite of tools described in this paper was used to not only assess various iterations of the new rucksack suspension system (Bryant et al, 1997b; 1997c; Reid et al, 1999b; Stevenson et al, 1998a). The aforementioned tools were also used throughout the iterative development process for the following:

- To optimize the design of the load-bearing vest shoulder straps in order to minimize pressure points when worn both alone and under the backpack (Bryant et al, 1997a; Reid et al, 1999a);
- To confirm the best vest storage pocket attachment and closure mechanisms to minimize relative motion between payload and the wearer’s body (Bryant et al, 1997a);
- To determine the optimal pack shoulder strap and hip belt shape, composition and construction, to minimize pressure points and optimize forces and moments acting on the body (Whiteside et al, 1999);
- To determine the optimal shoulder strap lower attachment point and angle so that horizontal lumbar shear forces could be minimized (Reid et al, 1998; 2000a);
- To determine the efficacy and optimal integration of lateral fiberglass suspension rods in the pack for most effective transfer of load to the hips (Reid et al, 1999c; 2000a);
- To identify compatibility problems and provide scientific support to the requirement for modification of underlying clothing layers to ensure compatibility with load-bearing equipment. (Skin pressure results have led to the decision to eliminate shoulder epaulettes on the combat uniform); and

- To contribute to the iterative design of the fragmentation protective vest by providing objective data relating to vest stiffness, compatibility with load-bearing equipment and loading of the spine (single shoulder closure versus dual symmetrical closures) (Reid et al, 2000c).

The development of the new load carriage system is described in more detail in a separate paper in these proceedings (Bossi & Tack, 2000). Other papers in these proceedings (Reid et al, 2000a; 2000b, Stevenson et al, 2000) provide results of specific testing of various iterations of the new load carriage system using the suite of objective tools described in this paper.

Future Research and Development Plans

Work is ongoing to improve the accuracy and reliability of a number of the objective biomechanical measures, specifically skin pressure measurements. Further human and simulator testing is planned for a wider range of commercial and military load carriage systems as part of the system validation process and to contribute to a better understanding of the relationship between designs and wearers. Work is ongoing to develop more advanced biomechanical models of load carriage that take into account some of the more sophisticated design features available in modern pack systems and that will consider the dynamic nature of human load carriage. Further development of an *in-situ* portable measurement device will support all of the foregoing efforts. Finally, Canada's suite of tools and design approach presented in this paper will continue to be used for the efficient objective assessment of load carriage system components, designs and underlying clothing conditions.

Conclusions

The tools described in this paper offer an efficient objective way to evaluate load-bearing clothing and equipment and their impact on users. They are intended to augment measures usually obtained with human-based testing and have already contributed to the effective iterative design and evaluation of a new load carriage system for the Canadian Forces as well as some of our allies. The suite of objective biomechanical measurement tools are on license and loan to Queen's University in Kingston, Ontario, Canada, and is available for use by both military and commercial load carriage system designers.

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Validation of Objective Based Measures and Development of a Performance-Based Ranking Method for Load Carriage Systems

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Summary

Standardized objective measurements for the evaluation of load carriage include the development of a load carriage simulator, a stiffness tester, and a suspension system characteristics tester. In addition, human-based methods have been developed by which the performance of load carriage systems undergoing evaluation in standardized military activities can be assessed. The purpose of this paper is to summarize three studies that examine the correlation between these objective and human-based measures.

In the first study, face validation was undertaken by comparing the outcome of measurements made in pack-based systems using a simple biomechanical model. In the second study, a direct comparison of objective measures to human based measures in a cohort of military volunteers was undertaken. In a final study, a ranking method was explored as a way of characterizing military load carriage systems.

Study 1. Face Validation

Four steps were required in the development of a simple face validation for objective measurements. The first was the development of a static biomechanical model. In the second step, a number of conventional packs were analyzed and predictions made for the force distribution in the pack and the torso. In the third step, a comparison was made between model results and the discomfort observed in a cohort of military subjects. Finally, design limits for shoulder and lumbar forces in pack systems were established.

Biomechanical Model

A simple statistically determinant model was developed to predict the forces distributed to the torso (MacNeil, 1995; Pelot et al., 1998; Stevenson et al., 1995). It was based on the geometry of strapping and lean angle associated with each system. A typical configuration is show in Figure 1. The lean angle is shown at which the weight vector acts vertically (Figure 1a). Two strap forces are shown: the lower strap force (T1) and the upper strap force (T2) are directed to the shoulder. A third force, Fh, is the reaction force at the lumbar region. Note that there is no waist belt associated with this design.

In Figure 1b, the shoulder model is shown as a simple pulley with friction. The scalar difference between the strap forces, T1 and T2 is the frictional force Ff. The shoulder reaction force is the negative of the vector sum of T1 and T2 acting through the centre of circle representing the shoulder.

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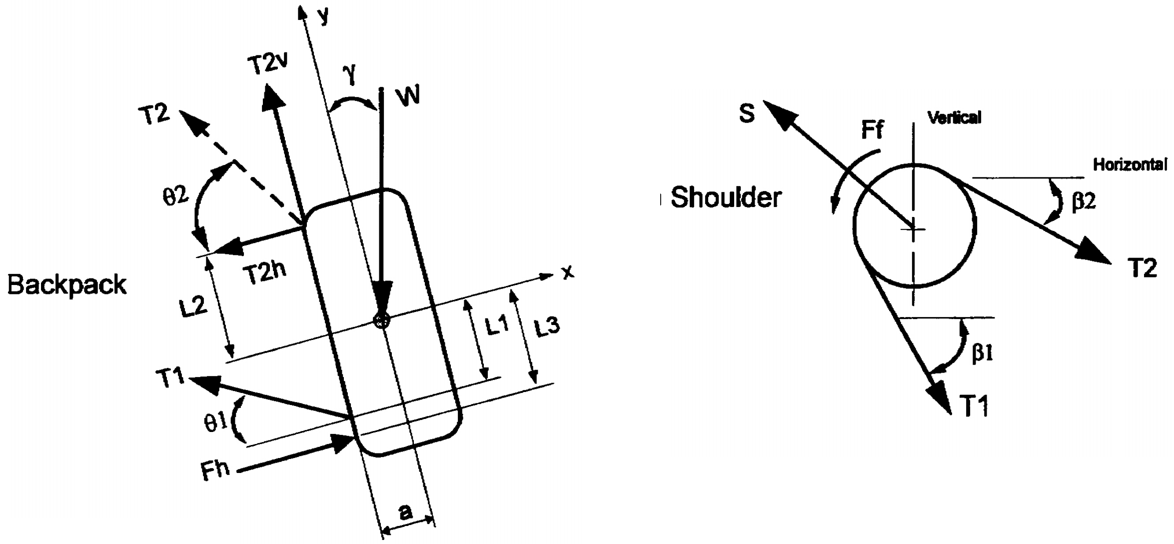

Figure 1. Biomechanical Model for Load Carriage. **(a)** Torso forces: T2 = upper strap, T1 = Lower strap, Fh = lumbar force, W = pack weight, γ = lean angle. **(b)** Shoulder forces: S = shoulder reaction force, Ff = friction force.

Table 1. Complete summary of biomechanical model results for the five test packs.

				Pack				
				A	**B**	**C**	**D**	**E**
Pack	Weight	(W)	Kg	32.1	33.1	32.7	31.8	31.8
	Inclination	(γ)	deg.	26.5	12.4	17.6	23.0	20.0
	COG offset	(a)	mm	122.9	133.1	116.7	105.8	127.1
Upper Strap	Horizontal Force	(T2h)	N	-3.0	89.7	41.2	8.4	39.0
	Vertical Force	(T2v)	N	137.9	182.3	218.4	201.9	209.9
	Location	(L2)	mm	192.9	51.2	325.9	187.6	238.0
Lower Strap	Angle	(θ1)	deg.	64.8	58.0	46.3	64.0	65.5
	Force	(T1)	N	160.0	159.0	120.8	94.4	91.0
	Location	(L1)	mm	350.5	271.7	-29.7	246.2	264.9
Lumbar Support	Force	(Fh)	N	206.1	243.7	221.7	171.5	183.3
	Location	(L3)	mm	287.3	248.3	89.2	227.1	206.8
Shoulder	Upper Strap Angle	(β2)	deg.	29.0	54.0	20.5	22.2	33.2
	Upper Strap Force	(T2)	N	138.0	203.2	222.3	202.0	213.5
	Lower Strap Angle	(β1)	deg.	37.3	45.2	29.0	41.1	45.5
	Lower Strap Force	(T1)	N	160.0	159.0	120.8	94.4	91.0
	Friction Force	(Ff)	N	-22.0	44.2	101.5	107.6	122.5
	Reaction Force	(S)	N	297.2	361.1	342.2	292.9	303.0
	Hor. Component	*(Sh)*	*N*	247.9	231.5	313.9	258.2	242.4
	Ver. Component	*(Sv)*	*N*	163.8	277.2	136.4	138.4	181.8
Load Distribution	Lumbar		%	29.1	16.1	20.9	22.0	20.0
	Shoulder		%	70.9	83.9	79.1	78.0	80.0
	Upper Strap	*(T2)*	%	39.5	48.9	61.0	58.0	59.0
	Lower Strap	*(T1)*	%	31.4	35.0	18.1	20.0	21.0

The input values for the model are the strap locations, the angle of the lower strap, the lean angle, the pack weight, and the shoulder angles. The output is the upper strap force and angle, the lumbar reaction force, and the shoulder reaction force. These result from a static balance of the forces and moments on the pack and on the shoulder.

Five packs were evaluated geometrically using this model. All were loaded with 32kg consistently at a centre of gravity located in the midpoint of the pack. Three military and two commercial systems were evaluated. The measured geometric variables and resultant forces are shown in Table 1.

Comparison to Soldier Evaluations

Testing was undertaken with 20 soldier volunteers from a variety of military occupations (Stevenson et al., 1995). All consented to the study using standard human ethics consent procedures. Soldiers undertook a 6 km march wearing the test packs loaded with 32kg. At the end of the march, soldiers provided combined ratings for perceived discomfort in the shoulder and lumbar areas. Scores were converted to percentage of all users reporting significant pain.

The correlation between forces and discomfort is shown in Figure 2. The shoulder force showed a $r^2 = 0.56$ and lumbar force showed a $r^2 = 0.81$ with respect to perceived discomfort. Extrapolating these values to zero perceived discomfort indicated design limits for these parameters: a maximum lumbar force of 135 N and a maximum shoulder force of 145 N (for each shoulder).

It is interesting to note that while the pack weighs 32 kg, a total of 450 N applied body force was observed even in the lowest case (Pack D). In other words, 40% greater body force was experienced than the gravitational force on the pack itself! Of this, 160 N (50% of the gravitational force) was experienced as a lumbar force. This is a transverse shear to the spine and is only present because the shoulder strapping is at an angle to the torso.

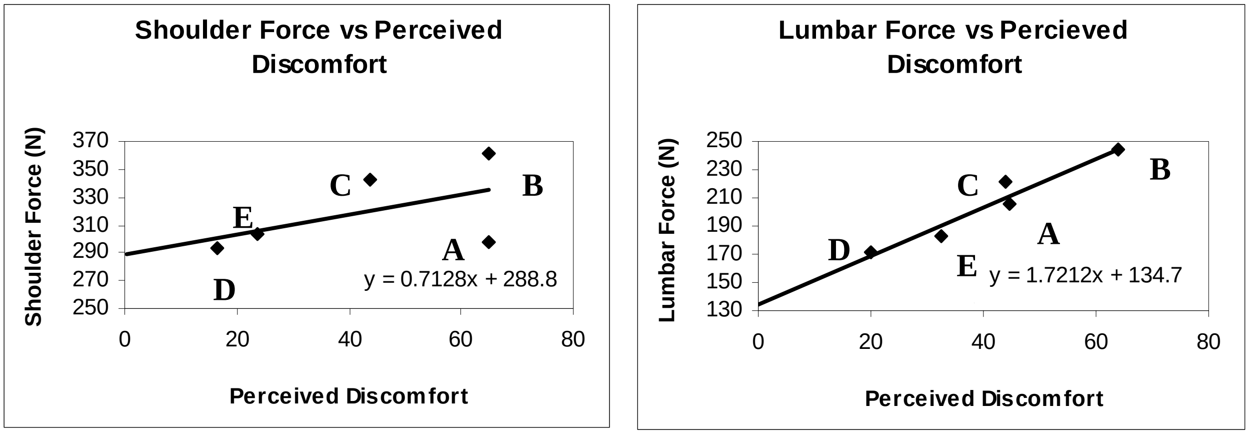

Figure 2. Body Forces versus Perceived Discomfort. (a) Shoulder forces (S in Figure 1 b). Total force is the sum of both shoulders. (b) Lumbar force (Fh in Figure 1 a).

Study 2. Construct Validity

A direct comparison between objective measures and subjective responses from soldiers was undertaken on nine military load carriage systems. Systems tested were from four countries and were evaluated in a variety of configurations that included rucksacks and webbing or load carriage vests.

Objective Tests

Objective tests undertaken were based on the load carriage (LC) simulator and the stiffness tester. In the load carriage simulator, a computer controlled torso is cycled in the vertical direction to simulate normal marching. Moments and forces at the hip are measured using a six-degree-of-freedom load cell. Displacement of the center of gravity of the pack with respect to the torso is measured using a Polhemus Inc. electromagnetic motion transducer (Fastrak™). Contact pressures at the anterior shoulder, posterior shoulder, upper lumbar and lower lumbar regions are measured using TekScan technology. This system is capable of measuring average contact pressures within 5% accuracy and peak pressures to 30% accuracy.

A second device was used to measure the stiffness of the pack system. The tester is capable of rotating the upper torso with respect to the lower torso in any of three directions while recording moment and angulation. Thus, torsional, lateral, and bending stiffness were obtained.

For each of the systems tested, the objective tests provided 39 measures of the mechanical characteristics of the system.

Human Performance Measures (FAST Trials)

Twenty-eight soldiers volunteered to undertake a series of activities (FAST[1] trials) testing mobility, function, agility, and comfort over a long march period (Bryant et al., 1997; Stevenson et al., 1997). Activities are indicated in the Table 2.

Table 2. Description of marching order testing activity stations (AS).

Activity Stations	Station Name	Description	Test Concept
1	Bent Balance Beam	- 10 m balance beam, 9 cm wide w/ 65 degree directional changes	Balance
	Boulder Hop	- 7 stones, 25 cm diameter w/90 degree directional changes	Balance
2	Straight Balance Beam	- 10 m balance beam, 9 cm wide	Balance
3	Fence Climb	- scale and descend 1.2 m fence	Agility
	Agility Run	- 10 pairs pylons (0.75 m apart) in slalom course over 10 m	Load Control
4	Side Slope Walk	- 7.5 m long w/ 26 degree side slope angle	Agility
	Forward Ramp Climb	- 4.5 m long w/ 21 degree angle of elevation	Load Control

At each station, soldiers were asked to rate acceptability in terms of balance, agility or load control on a scale of 1-6, 6 being acceptable. In addition, comfort was rated on a scale of 1-9, 9 indicating extreme discomfort. Tests were also undertaken to evaluate the ability to provide a range of motion for the hands and torso during the activities indicated in Table 3.

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[1] FAST refers to First Assessment and Standardized Testing

Table 3. Description of marching order static tasks test.

Task	Task Name	Description
1	Hands above head	- reach both arms above head together - drop one arm, drop second arm, raise first arm, raise second arm
2	Hands in front	- reach both arms in front together - drop one arm, drop second arm, reach first arm, reach second arm
3	Forward flexion	- bend forward from waist, weapon in front - return to neutral, repeat
4	Lateral bending	- bend sideways at waist with weapon resting on floor - return to neutral, repeat to opposite side
5	Rotation	- rotate at waist with weapon in front - return to neutral, repeat to opposite side
6	Canteen access	- remove canteen from pouch in standing position - return canteen to pouch, repeat
7	Respirator Access	- remove gas mask from respirator pouch in standing position - return mask to pouch, repeat
8	Sit down	- move from standing to seated position
9	Lie in prone position	- move from seated to prone position
10	Emergency doff	- return to standing position - emergency doff pack with available quick release system

During the FAST trial circuit, soldiers marched a total of 6 km in one (1) km intervals. At the end of the circuit, ratings for discomfort and acceptability were also obtained for the march.

Twenty-eight subjects, all male, with an average age of 25.5 years, service duration of 5.4 years, height 1.78m and weight 82.1 kg, participated in the experiment. An incomplete block design provided a mean value of 12 assessments for each system. Each soldier only evaluated two systems and different soldiers in different pairings evaluated systems.

Statistical Analysis

A Pearson correlation table was developed for all measurements. A value of $r = 0.66$ indicated a correlation of $p < .05$ as shown in Table 4. LC-simulator measurements (including the stiffness measurements) are indicated to correlate significantly with FAST trial measurements by an asterisk. In several cases, correlations were found among single variables from the standardized measures and multiple human based measurements.

Table 4. Correlated load carriage and FAST trials measures.

Simulator Measures		Correlated Human Factors Measurements
Displacement (mm)	x *	Posterior Hip Discomfort
	y	
	z *	Posterior Hip Discomfort
	r *	Posterior Hip Discomfort
Moment (Avg, Nm/kg)	x	
	y *	Forward Flexion Mobility, Overall Comfort, Overall Fit
	z	
	r	
Force (Avg, N/kg)	x	
	y *	Front Mobility, Overhead Mobility, Posterior Shoulder Discomfort, March Thermal Comfort
	z *	Front Mobility, Overhead Mobility, March Thermal Comfort
	r	
Moment (Amp, Nm/kg)	x *	Torsional Mobility, Overall Mobility, Lie Function, Balance, Agility, Anterior Shoulder Discomfort, March Acceptability, March Comfort
	y	
	z *	Front Mobility
	r *	Posterior Neck Discomfort
Force (Amp, N/kg)	x	
	y	
	z *	Lie Function, Load Control, March Acceptability, March Integration, Overall Balance, Overall Comfort, Overall Fit, Overall Maneuverability
	r *	Load Control, March Integration
Shoulder Pressure (ANT)	Av (kPa)*	Posterior Hip Discomfort
	Pk (kPa) *	Doffing Function
	PDI *	Doffing Function
	F(N) *	Posterior Neck Discomfort
Shoulder Pressure POST	Av (kPa)	
	Pk(kPa) *	Doffing Function
	PDI	
	F(N)	
Lumbar Pressure UPPER	Av (kPa)	
	Pk (kPa)	
	PDI	
	F(N) *	Posterior Discomfort
Lumbar Pressure (LOW)	Av (kPa)	
	Pk (kPa)	
	PDI *	Front Mobility, Posterior Discomfort
	F(N)	
Stiffness (Nm/deg)	Torsion*	Overhead Mobility, Front Mobility
	Flexion*	Combined Function, Posterior Neck Discomfort, Low Back Discomfort
	Side *	Front Mobility, Anterior Shoulder Discomfort, Anterior Hip Discomfort

Shoulder Pressure Correlations

A correlation analysis was performed to determine a maximum allowable average pressure for the shoulder region. LC-simulator data for the anterior and posterior pressure sensors were combined and the average pressure in these regions provided the independent variable. Perceived discomfort rating reported by soldiers wearing the corresponding pack was the dependent variable.

Results showed that 95% of soldiers reported discomfort when the average shoulder pressure exceeded 20 kPa. Similarly, 90% reported discomfort at pressures exceeding 18 kPa. These values are greater than the 14 kPa, the physiological limit for blood flow occlusion.

Application to Load Carriage System Evaluation

In order to apply these findings to the evaluation of the acceptability of load carriage systems, it is necessary to compare soldier preferences to predictions of the standardized measures. Load carriage systems were selected for assessment based on their overall rating and performance in standard march. Ratings for two preferred systems (A and B) and two less preferred systems (C and D) are shown in Figure 3. A high score indicates a more preferred system.

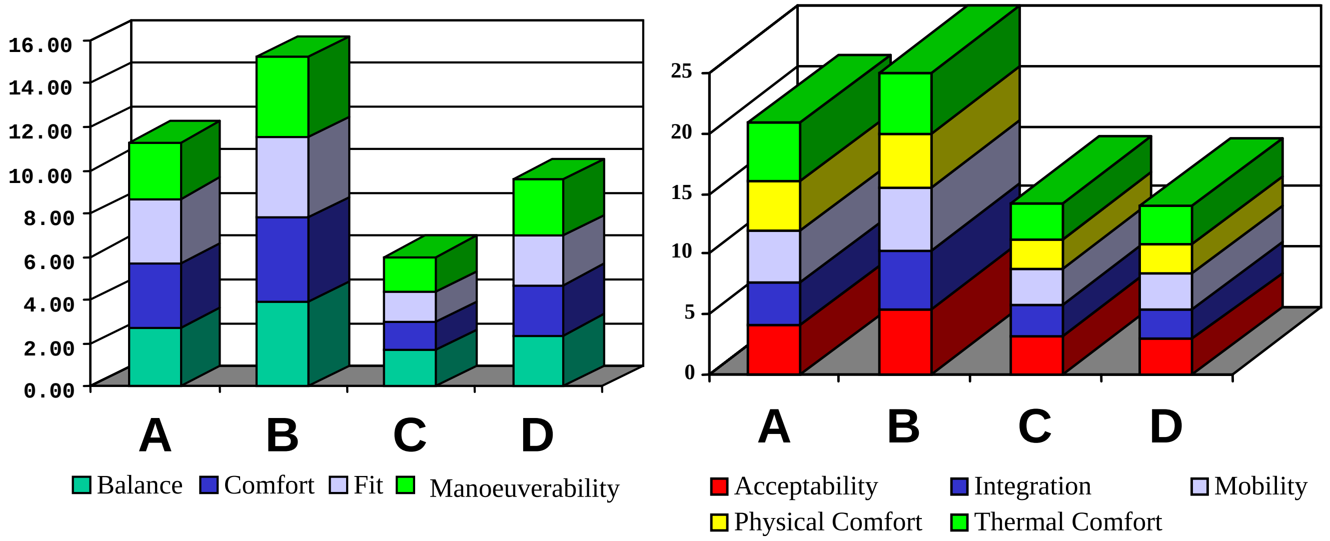

Figure 3. Overall Ratings for Four Systems. A and B were preferred systems, C and D were less preferred. (a) Overall ratings. (b) Extended march ratings.

Representative LC simulator results are shown in Figure 4. In Figure 4a, relative displacements for pack C in the forward direction exceed the 90th percentile for all packs measured in the study. Similar observations can be made for forward and vertical reaction moments and forces as shown in Figures 4b and 4c. This corresponds to the low overall ratings provided by the soldiers.

Observation of skin contact pressures in the shoulder region and back region are shown in Figure 5. Interestingly, all systems exceeded the 20 kPa discomfort rating in some region. Pack B, although highly rated, created high skin contact pressures both in the shoulder and in upper lumbar regions. However, soldiers apparently valued its ability in other areas, especially maneuverability, establishing a superior overall rating. Pack C, in contrast, indicated high discomfort ratings as well as poor ratings for maneuverability.

Figure 4a: LC Simulator – Relative Displacements (mm)

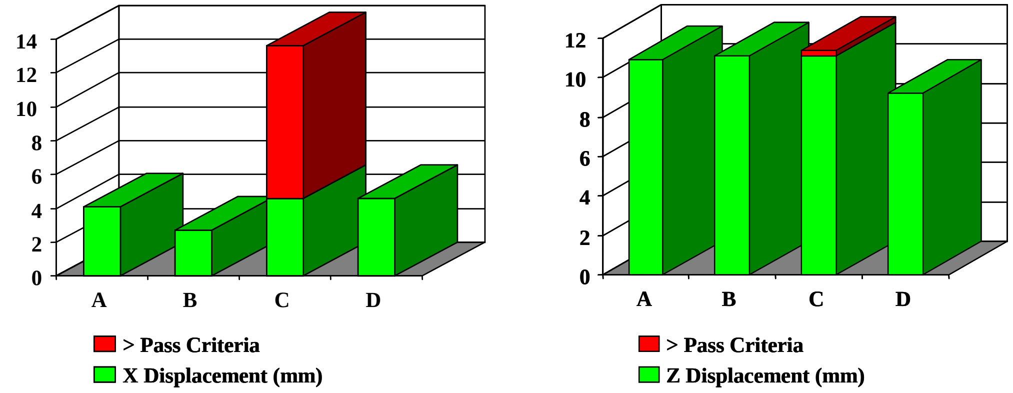

Figure 4b: LC Simulator – Reaction Moments (Nm/kg)

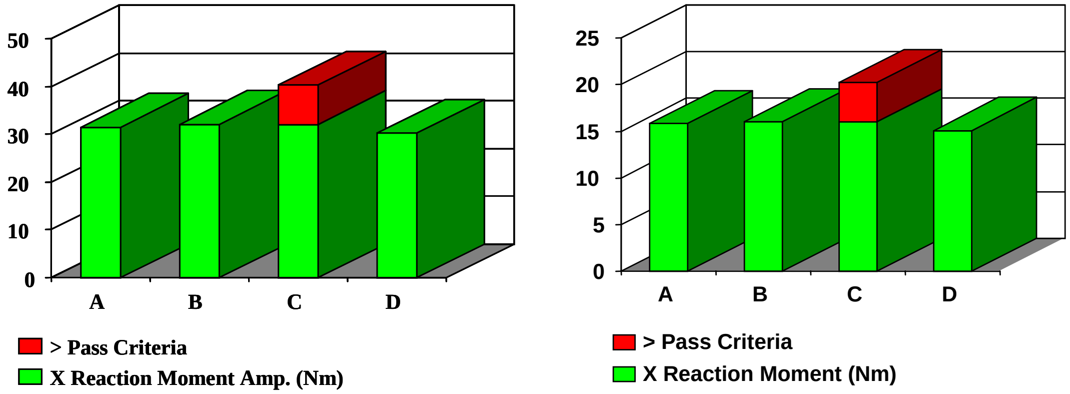

Figure 4c: LC Simulator – Reaction Forces (N/kg)

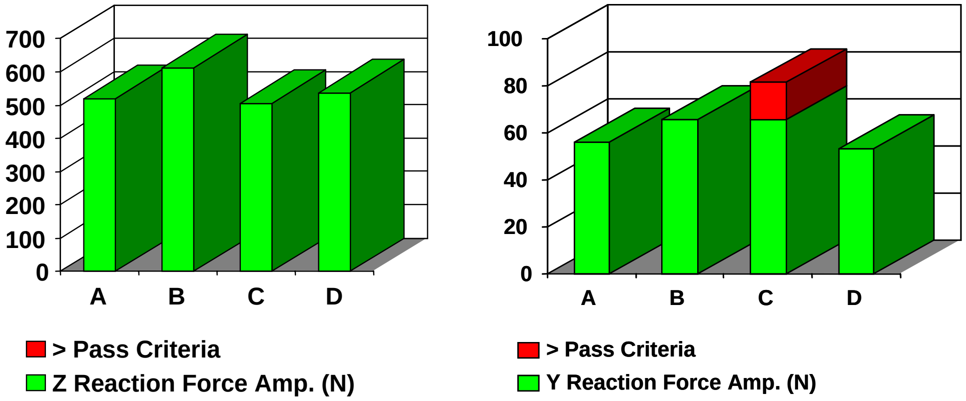

Figure 4. Relative Displacements, Moments and Forces for Four Systems. (a) Relative anteroposterior displacements (x) and vertical displacements (z) (mm). (b) Reaction moments about transverse axis (Nm). (c) Vertical reaction forces (z) and side reaction forces (y) (N). Pack C often fails the pass criteria.

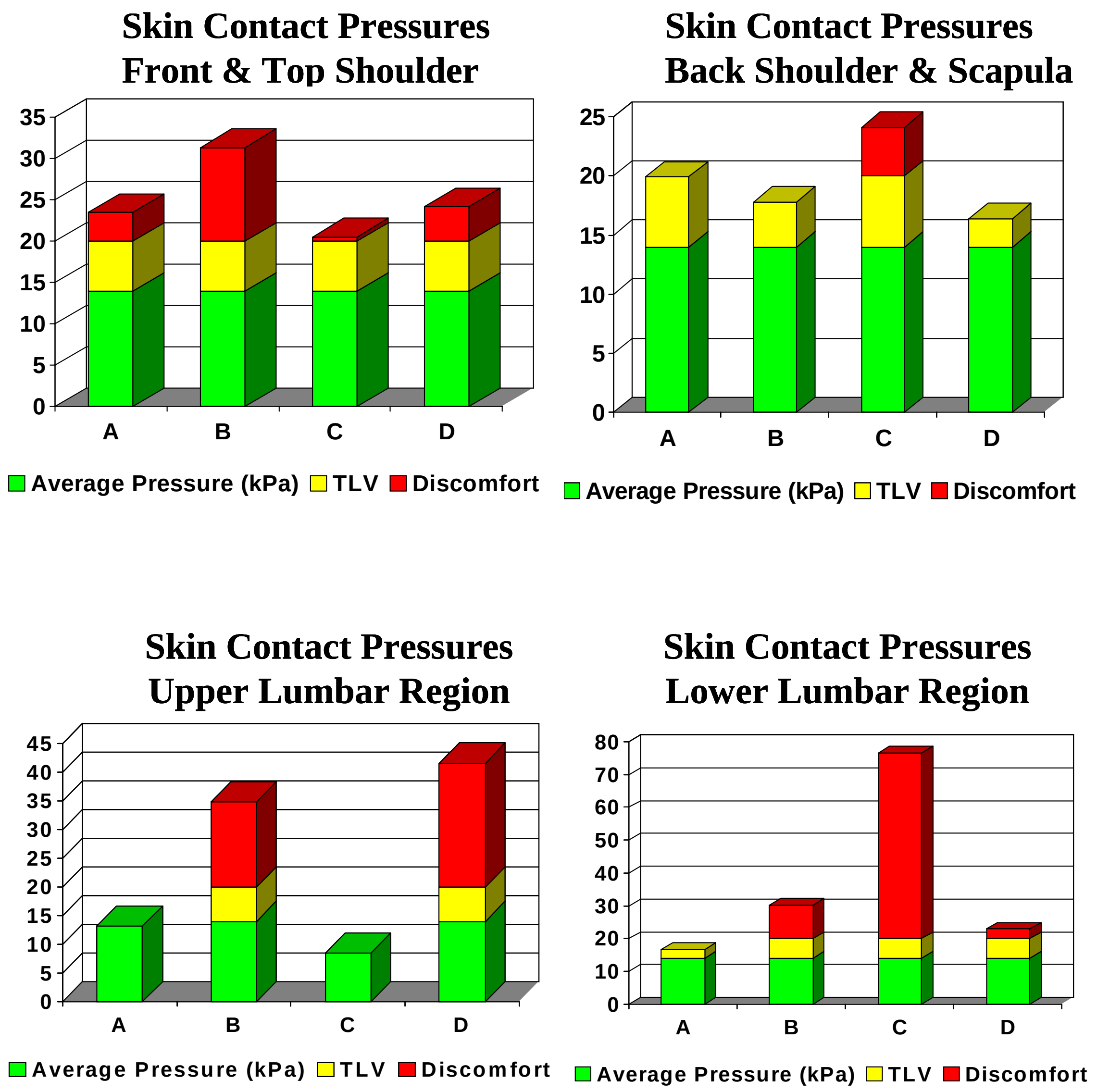

Figure 5. Contact Pressures for Shoulder and Back. Discomfort pressure = 20 kPa, TLV = 14 kPa. Average pressures shown for all cases. (a) Front and top shoulder. (b) Back shoulder and scapula. (c) Upper lumbar region. (d) Lower lumbar region.

Study 3. Performance-Based Ranking System

A third study was undertaken in which factor analysis was performed on all measured values of Study 2 (Doan, 1998). In particular, this study was undertaken to reconcile some of the tradeoffs associated with good performance in some measures and poor performance in others when establishing an overall rating for a load carriage system.

Factor Analysis

Factor analysis is a method by which the correlation among all measured variables are used to group highly correlated variables together into so-called factors. These factors are then manipulated as new variables that have a low correlation with each other.

From Study 2, 76 variables from the LC-simulator and FAST trials were produced for each load carriage system. These were reduced to 3 factors that accounted for a total of 71.1% of the variance in the measurements as indicated in Table 5.

Table 5. Results of the factor analysis on the total data set.

FACTOR	NOMENCLATURE	VARIABLES	VARIANCE
I	Balance	**Trunk/Body Motions** (Lateral bending, Torsional Rotation, Lie Down)	27.4 %
		Load Transfer (Posterior Shoulder Discomfort, Overall Comfort, General Load Control, Vertical Force Amplitude)	
II	Load Control	**LCS Kinematics** (A.P Displacement, Transverse Displacement)	23.4 %
		LCS Kinetics (A/P Force Average & Amplitude, Transverse Moment Amplitude, Lower Lumbar contact Force)	
III	Shoulder and Arm Restriction	**Reach Measures** (Hands above Head, Hands in Front)	20.3 %
		Shoulder Restriction (Vertical Force Average, Torsional Stiffness, Thermal Comfort)	
Total			**71.1 %**

Factor 1 described the balance and general ability to move with the pack in place. Variables included lateral bending, torsional rotation, and lying down activities, as well as measures for posterior shoulder discomfort, overall comfort, general load control, and the vertical force amplitude.

The second factor was associated with physical variables involved with load control. These included A/P displacement, transverse displacement and corresponding amplitudes for forces and moments. In addition the lower lumbar contact force loaded on this factor.

The final factor combined both human and LC-simulator measurements in features associated with shoulder and arm motion. Variables included hands above the head and in front activities, as well as the average vertical force, torsional stiffness, and overall thermal comfort.

Expert Ratings

In order to compare these factors to overall ratings, three independent military load carriage system experts were surveyed. The experts rated the systems on a 3-point scale as unacceptable, acceptable or good. These ratings were combined into Friedman ANOVA estimate of inter-correlation between judges.

Total factor scores were based on the combined measurements of the variables associated with each factor. A factor score of zero is exactly at the mean for that factor. A score of –2, for example, is two standard deviations below the mean score for that factor.

The overall rating between the judges and the total factor scores is shown in Figure 7. For factor scores plus and minus 1.5, there was no consensus among ratings indicating that other criteria were used by experts in ranking. However, for scores outside this limit, the factor scores were consistent with those of the judges. The poorest rated system had a factor score of –1.84, while the highest rated system had a factor score of 3.06. This indicates similarity between the opinions of expert observers and the measures made in LC-simulator and human trials.

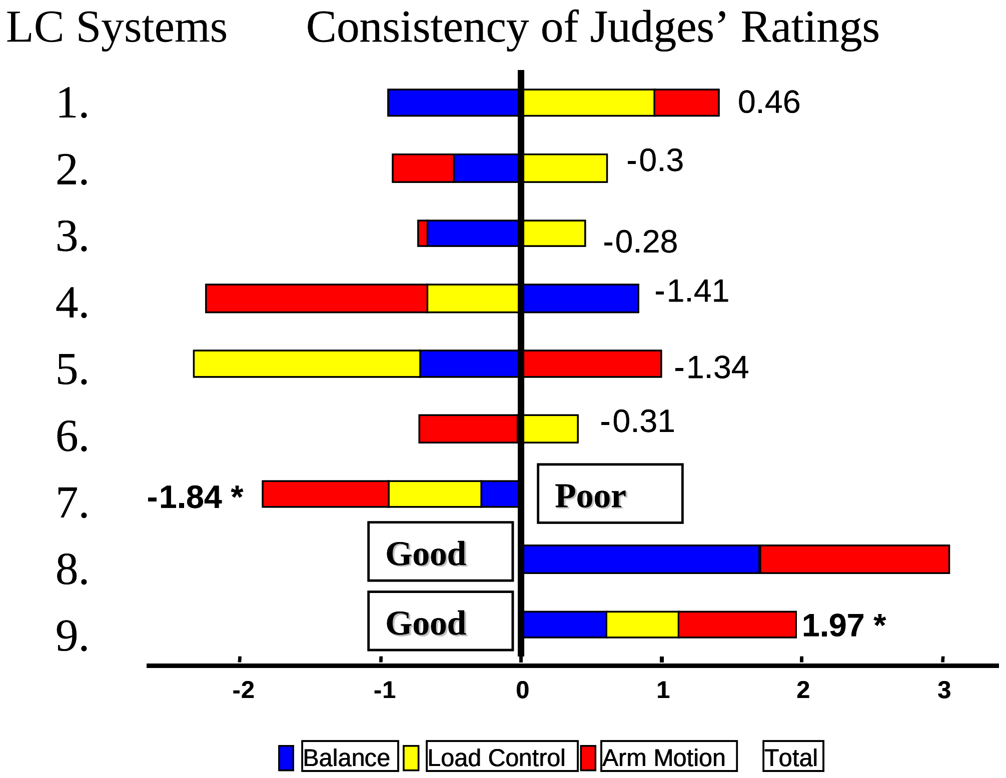

Figure 7. Load Carriage System Ratings. Total factor scores are indicated by number for each of the nine systems evaluated. The three lower systems were all rated as Poor or Good consistently by all experts. These also had the lowest and highest factor scores respectively.

Conclusions

Based on the results of the validation studies, the following conclusions are warranted:

- The face validity of standardized measurements for load carriage systems has been demonstrated using a simple biomechanical model. Results indicate a force limit of 145 N per shoulder and a lumbar force limit of 135 N for extended march conditions under heavy (32 kg) loads.
- There is a significant correlation of standardized measures and human measures as reported by soldiers undergoing simulated military activities. These measurements can be used to establish performance benchmarks for load carriage systems undergoing standardized testing.
- Average shoulder contact pressures of 20 kPa result in reported discomfort by 95% of soldiers undergoing extended march under heavy (24 kg) loads.
- Factor scores indicate that three factors can explain 71% of the variance in standardized tests. These scores indicate distinctly good or distinctly poor performance. However, rankings do not agree with expert observer rankings for near-average performance.
- A two-tier ranking system is indicated. In the first, standardized measures should be used to screen in or screen out particular designs. In the second stage, operational definitions and specific soldier preferences

should be used to make selection based on performance requirements rather than physical attributes of the system.

Recommendations

The validation of the objective measures was completed in stages and with a limited number of load carriage systems to evaluate. It would be wise to repeat this study with a larger sample of systems both for face validity, construct validity and to develop a ranking system. It is anticipated that a confirmatory sample would help delineate the necessary features of a superior load carriage system for military applications. However, it will be necessary to complete human trials to gather the necessary subjective information on features and functions of the system in order to complete the rating system based on all of the aspects needed to determine a superior load carriage system.

Acknowledgement

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Lessons Learned During the Development of the Modular Lightweight Load-Carrying Equipment (MOLLE) System

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Summary

The US Army conducted a comprehensive front-end analysis (FEA) which surveyed key users and identified critical issues and requirements for developing new load bearing equipment (LBE). From the FEA a detailed users' operational requirements document (ORD) was developed and from both the FEA and ORD the MOLLE emerged. The results of these efforts reveal several things about the methods used, as well as, issues and features of the system developed. This paper discusses the lessons learned about test methodology and features of LBEs found to work or not work for the dismounted combatant.

Introduction

In 1988, a new internal frame, load-carrying system was adopted by the U.S. Army. The design was based on commercial backpacks modified for military use with the addition of a special fighting vest and a detachable patrol pack. The original focus was to develop a load-carrying system for use in cold weather. However, in the final analysis, the US Army selected the new internal frame LBE as a replacement for the external framed All-purpose Lightweight Individual Carrying Equipment or ALICE system. Production and distribution started in 1990 but by 1993 it was clearly evident that the new internal frame pack was unacceptable to a large number of combat personnel.

Although a key problem with the internal frame was durability due to poor quality control in production, it was also judged to have basic design flaws. Based on a survey of users by the US Army Training and Doctrine Command (TRADOC), soldiers claimed the pack was too hot against the back in warm climates, and was unstable and uncomfortable when heavily loaded. While many of the features of the system were liked (e.g., the patrol pack, and capacity of the main pack), it was judged not to meet the overall requirements of the Army. In spite of this rejection, most units surveyed (6 of 9), still favored having both load-carrying systems: the ALICE for warm and temperate climates, and the internal frame system for cold weather operations. This was not to be.

In March 1994, the TRADOC System Manager for the Soldier (TSM-Soldier), the Combat Developer at the U.S. Army Infantry School, the Program Manager (PM)-Soldier, and the U.S. Marine Corps Systems Command, called for a front-end analysis (FEA). The FEA was to determine what the Army and Marine Corps load bearing system design should be (ref. 1). The FEA was used in drafting a new user requirement document and initiating the development of a modular load-carrying system that ultimately became the Modular Lightweight Load-carrying Equipment (MOLLE).

This paper presents summaries of the FEA survey and the results from the subsequent series of tests conducted during MOLLE development. While test methodology is presented, the main focus is on addressing and identifying important features of load-bearing equipment important to infantrymen. This is followed by discussion as to why engineering efforts continued on retaining certain features, in spite of the fact tests showed these features were not performing well and were not universally accepted by users.

Paper presented at the RTO HFM Specialists' Meeting on "Soldier Mobility: Innovations in Load Carriage System Design and Evaluation", held in Kingston, Canada, 27-29 June 2000, and published in RTO MP-056.

Approach

For the FEA, a user questionnaire and a group interview form were developed from statements collected from soldiers and marines as well as from information obtained from the 1988 technology demonstration on Lightening the Soldier's Load (ref. 2). Questionnaire items asked about the type of LBE in current use, types of problems encountered and solicited recommendations for improving LBEs. A small pilot test was run to refine wording of the questions and statements. Questionnaire items were pre-structured statements based on all the issues identified and were either numerically scaled 0 to 4 (None to A Lot), verbally scaled Strongly Agree to Strongly Disagree or merely check-off lists of items or issues. At the end of the questionnaire respondents were asked to write down any suggestions they had for improvements. The final questionnaire was used as a framework for the user-focus-groups referred to here as "muddy boot" teams.

Over a period of seven months questionnaires were distributed to over 2,000 soldiers and marines by U.S. Army Natick Operational Forces Group during their routine surveys of users of Natick developed food, clothing, shelters, and individual equipment items. Five US Army posts (Forts Bragg, Campbell, Drum, Hood and Lewis) and two US Marine Corps sites (Camps Mabry and Lejeune) were visited. All those surveyed had experience with the ALICE and 40 percent also had experience with the recently introduced internal frame system. Highlights of the results are presented below. In addition, results from a series of eight developmental tests (unpublished) on MOLLE are presented. These tests involved experienced soldiers who evaluated candidate systems during simulated tactical movements in the field and laboratory.

For the developmental tests, a series of short but comprehensive human factors (HF) questionnaires was developed, tailored to each test condition. The questionnaire items (see appendix) covered the main issues addressed in the FEA as well as the official Operational Requirements Document (ref. 3). Each item was a phrase relating to a required or desired feature or performance characteristic. A quantitative rating scale followed each phrase. Various scales were used and wording changes were introduced from test to test but results show the questionnaires provided highly consistent results across tests. Changes in scale and wording appear to have had little, if any impact on results. That is, the same LBE design problems were identified in each test. Quantitative analysis of the scaled questionnaire was complimented by the qualitative written comments by the soldiers at the end of each questionnaire and statements made during the focus group.

These developmental tests involved experienced volunteers performing a number of load-carrying activities such as a road march, individual movement actions and/or simulated squad patrols or ambushes. During these activities the volunteers were required to don and doff loads repeatedly. Most activities took several hours and were followed by the questionnaire and team interview session. These tests were conducted at various locations and under varied conditions. One test, for example, was conducted in tropical heat with soldiers stationed in Panama and another in the Natick arctic cold chamber with experienced cold weather soldiers from Alaska.

During some of the early tests, MOLLE was tested along side other candidate modular systems while in the later tests MOLLE was either tested alone or with ALICE. In all tests volunteers were asked to rate MOLLE against their current LBE, viz., the ALICE. Upon completing the individual questionnaire, the team was brought together for a focus-group discussion. In most tests, the field actions and focus group discussions were video recorded for later review and analysis. The FEA and the developmental tests are briefly described below along with brief summaries of results, followed by discussion of lessons learned.

Results

Front End Analysis 1995

The FEA survey resulted in 1,280 fully completed questionnaires by soldiers and marines from eight military specialties. Fifty-six percent of the respondents were Combat Infantrymen, 14% Combat Engineers, 8% Medics and the remainder were Communications, Chemical, Mechanic, and other support specialists.

The respondents were given 32 statements about their current load bearing system and asked to indicate whether they agreed or disagreed, slightly or strongly, with the statement. The respondents were also asked to suggest improvements they would recommend for a future load-carrying system.

In addition to the survey, two "muddy boot" panels (n = 5 & 7) were conducted at Fort Benning, Georgia in September 1994, where each panel discussed, independently, the same set of questions as presented in the questionnaire. The two panels were then brought together to review their judgements and to arrive at a consensus about the requirements of a new load-carrying system.

The key findings of the FEA include a call for slightly more rucksack capacity and a capability to configure loads for different soldiers and missions. While it was recognized that greater capacity would mean a greater potential to over-load the soldier, the need to hold specialized items and the ability to quickly arrange and extract needed items from the pack were judged more important. Since heavy loads are nearly impossible to avoid during most real world missions, durability of the system and the added support provided by an external frame were identified as important requirements. The high rating on the ability-to-reconfigure requirement and the need to tailor loads strongly suggested the system should be modular. The emphasis on modularity was supported by the earlier effort of the Lightening the Soldier's Load Technology Demonstration of 1988. That demo concluded that making equipment modular allows fighting units to reduce loads through mission tailoring in theater. The dilemma, however, was that most removable components tend to lack the stability of fixed, sewn-on components. Thus, if the modularity concept was to work, an attachment mechanism, for providing better stability of components, was needed.

Focus was also given to the need for quick release of the main pack. While quick removal of the main rucksack has been a long-time desired feature, extra emphasis was given to this during the FEA. The FEA called for the development of a quick release mechanism. Discussions on the ease of donning and doffing of the rucksack lead to concerns about multiple belts and harnesses and the desire to simplify the system. This was reinforced by the expressed desire to make the load-carrying system more compatible with other worn equipment by eliminating competing belts and straps. For increased comfort, users asked for more padding, particularly on the shoulder straps. However, it was recognized that soldiers tended not to use their hip belts for tactical reasons (so they can quick drop the main pack when fired upon). Hence, there was a need for a more functional hip belt to help distribute the load but also allowed the pack to be dropped quickly. Thus, the FEA recommended the concept of a padded hip belt and other features for distributing or adjusting the load during prolonged road marches plus a quick release feature.

The FEA also presented a list of other issues, features, and performance requirements, such as camouflage, noise attenuation, water resistance, shouldering of the weapon, ability to clean, compatibility with other equipment, and so on. The FEA draft Requirements Document included nearly all of these with varying emphases. From this, TRADOC developed the official users' ORD for a new modular load-carrying system (ref. 3).

MOLLE 1997

The MOLLE started out as a load-carrying system for the US Marine Corps and incorporated many, if not all, of the required and desired features called for in the Army's FEA and ORD. Chief among these were modular pouches, a durable external frame with a reliable and durable quick release, a padded hip belt, and the elimination of the second belt of the load-bearing harness. The main pack and added pouches of the MOLLE had a capacity slightly greater than ALICE 's large rucksack and included special sized pouches to accommodate items for different users and missions. In addition, the system included the popular patrol pack from the previous system, a butt pack and fighting vest that allowed attachment of ammunition and other pouches. The real key to making the MOLLE a viable alternative was the innovative design of the attachment mechanism for modular pouches that gives each pouch a sewn-on quality, yet allows easy removal or re-attached to new locations on the load-carrying system. The other promising feature was the highly durable and reliable quick release mechanism for rapid dropping of the main pack. Prior to MOLLE no system worked well enough to be seriously considered to replace the ALICE.

Fort Campbell, Kentucky 1997

The first field evaluation of the MOLLE and another candidate was conducted at Fort Campbell in October 1997. Twelve US Army Rangers ran through an obstacle course wearing the full MOLLE or just the fighting vest. Actions included climbing under, over and through obstacles, low crawling, stepping or vaulting over barriers, balanced walking and a 5 kilometer march with a 23 kg weighted load. Between obstacles the soldiers had to doff and re-don the main rucksack several times. Following these activities the volunteers completed the Natick HF questionnaire and participated in the group discussions to compare MOLLE with ALICE and the competing system. The MOLLE was rated higher than the competitive system and only slightly higher than the ALICE. MOLLE scored highest on Modularity, Quick-Release, Ability to Vent, Quality of Closures, Holding Capacity, Feel While Walking, Stability of Pouches, Comfort with Loads and Durability. It scored low on Ability to Don Quickly, Quietness and Ability to Fire Weapon Prone. Based on these results the MOLLE was modified to make it easier to don by changing the probe design and shortening the frame.

Fort Benning, Georgia 1997

The second evaluation of MOLLE was again conducted with a group of US Army Rangers (n=13) at Fort Benning in December 1997. Prior to conducting mock patrols and ambushes in the field, the soldiers were given instruction and fitted on the MOLLE and practiced donning and doffing the ruck many times. They then spent much of the day in the field conducting various tactical movements. At night they went through night maneuvers to evaluate using the system in the dark. Following these activities they completed the Natick HF questionnaire and participated in focus-group discussions. The results again show the soldiers preferred MOLLE over the competitive system and only slightly over ALICE. They rated the modularity and pouch design very high. The loaded ruck was judged as highly stable and the frame durable. They liked the ability to shift the load while moving. Again, their greatest concern was the frame locking mechanism, time to don the rucksack, top-heaviness of a full load and the noise made by frame. There also were safety concerns (e.g., fingers getting caught in the locking mechanism). The MOLLE was again modified to address some of these issues.

Fort Kobbe, Panama 1998

The MOLLE was then evaluated by a U.S. Army test agency at Fort Kobbe, Panama in June of 1998. Here 49 soldiers used the MOLLE over several weeks, after which they were given a series of questionnaires including Natick’s human factors questionnaire. The scale of the questionnaire was changed from a 0 to 5 scale to a 3+ to -3 scale to accommodate the tester in Panama. Wording was changed to match the new scale. The data show much the same results with highest ratings for the design of pouches, stability of pouches, clean-ability, repair-ability, capacity, reconfigure-ability, range of motion and feel while walking. The lowest ratings were for the frame-locking mechanism, re-donning times, problems low crawling, and balance with heavy loads. Nearly all the negative ratings related to the quick-release attachment system.

Natick Soldier Center 1998

Based on anecdotal reports from US Marines, MOLLE was judged not to be operable with standard issue army gloves. Therefore, a series of timed tests were conducted at Natick comparing the MOLLE and ALICE with volunteers (n=6) wearing gloves (July 1998). The results show the volunteers could operate the MOLLE as well as they could the ALICE. In fact, for many activities, volunteers performed better with MOLLE than ALICE due to improvements in snaps and fasteners. The only aspect of MOLLE that was worse than ALICE was the soldiers' donning of the rucksack. However, this was true both with and without gloves. Once again, the frame quick-release attachment was found to be a problem for the user in spite of a number of improvements. While some soldiers could re-don the pack reliably, there were many others who were unable to do so with any consistency[*].

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[*] Although there is insufficient evidence at this point, observations suggested that anthropometric features of individual soldiers might play a role in the ease or difficulty of donning the MOLLE. It may be that individuals with certain back

Natick Cold Chamber 1998

In September 1998 Natick conducted a week long test of the MOLLE with the new Interceptor body armor in the arctic cold chamber using volunteer soldiers from Fort Richardson, Alaska. The volunteers brought their own cold weather gear and ALICE systems for comparison. Following several days donning and doffing loads, conducting tactical movements and marching in the cold (-23.3 C, wind-speed 4.1 kph) with 23 kg loads the soldiers completed the Natick HF questionnaire modified for cold weather operations, and participated in a team review. The results parallel previous tests. These soldiers rated Tailor-ability and Stability very high. They also liked the capacity it had to hold bulky cold weather gear. As in previous tests, these soldiers found the re-donning of the MOLLE pack quite difficult and gave a low rating to the detachable frame concept.

Fort Polk, Louisiana 1999

A variation of the MOLLE fighting vest (the "Rack") with shorter frame and "attached" or fixed belt was tested at Fort Polk with US Army Rangers during a field exercise in April 1999. The attached frame meant there was no quick release with the frame attached much like the ALICE. Forty-nine out of seventy soldiers completed the Natick HF questionnaires which also included questions on amount of time worn and usefulness of specific features. To accommodate various equipment items, special modular features were added to the MOLLE including a Leg Bag, PRC 126 Radio Pouch, Saber Radio Pouch, Map Cover, Claymore Mine Flap, Canteen Pouch, Snivel Pouch (butt pack), SINCGARS Radio Flap, and a Drinking Pack. The results mirror many of the earlier tests, with MOLLE receiving high scores on Ability to Reconfigure, Design of Pockets and Pouches, Durability, Closures, Stability of Pouches, and Comfort while Walking. Low scores were obtained on Ability to Fire Weapon in Prone Position, and Put-on and Take-off Quickly. In spite of the shortened frame, there were still complaints of the frame being too long. More accommodations were needed for soldiers with shorter body dimensions. While MOLLE continued to be rated low for ability to fire weapon in prone position, many soldiers admitted they would not expect to fire prone with a fully loaded rucksack. Furthermore, no one knew of a backpack that would allow soldiers to aim and fire their rifles prone. Thus, it appears this requirement was not to be met from the start.

Natick Soldier Center 1999

The last and most recent test of MOLLE using the Natick HF questionnaire was conducted in October 1999 and involved the evaluation of alternative frame attachments. These were, 1) the standard MOLLE single-probe quick-release; 2) a modified single- probe quick-release; 3) a double probe quick-release and 4) a fixed belt-to-frame system. Six US Army Rangers went through simulated squad movements in a forest area near Natick as well as an obstacle course and a 2-mile march. The volunteers carried 23kg and practiced donning and doffing the load repeatedly. In addition to being timed on the various designs, they completed the HF questionnaire and rated each system. For this test the scale was changed from a range of +3 to -3 to a wider range of +5 to -5. This allowed the user a greater range of responses and provided greater sensitivity during analysis.

The results show that the fixed belt version was rated extremely high relative to all other quick release versions. In this test, the volunteers first evaluated all the quick release candidates before they were given the fixed belt version of MOLLE. The ratings for the two-point quick release frame were higher than the one point for Balance and Stability. The two single point versions were rated higher on Comfort. Then, after the soldiers used the fixed belt version, the MOLLE was rated significantly higher on almost everything. The results show the soldiers overwhelmingly preferred the fixed belt above any of the quick releases. Every volunteer was ready to trade his ALICE for this version of MOLLE on the spot.

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and arm dimensions, as well as certain curvatures of the back have more difficulty donning MOLLE. To fully answer this would require a sizeable army-wide anthropometric study.

Discussion

In the early phases of the program to develop a new load-carrying system for the US Army, a comprehensive front-end analysis (FEA) was conducted which surveyed key users and identified a critical set of issues and requirements. From the FEA a detailed users' operational requirements document (ORD) was developed and from both the FEA and ORD the MOLLE emerged. These efforts reveal several things about the measurement methodology used, as well as, issues and features important to soldiers. The discussion below begins with some lessons learned about the measurement methodology used and is followed by discussion on which features of LBEs were found to work for the dismounted combatant and which did not.

Questionnaires and Focus Groups

Throughout this program short, simple, yet, comprehensive questionnaires were used in combination with relevant field and laboratory activities. Experienced users (soldiers) worked with engineers to arrive at designs that met their requirements. Although, from test to test, the questionnaires varied in minor ways in terms of wording and scales, the results were comparable across tests. In spite of the changes, the questionnaires identified the same strong and weak points of the load-carrying system that ultimately allowed engineers to tweak the design toward needed improvements. This was possible because of the combined use of fixed questions, written comments and focus group discussions. The combined data gave the design team confidence about the results. Furthermore, quantitative scaling of items allowed statistical analysis in support of decision making.

The lesson learned was that more important than scaling was the content and conditions of the tests and that testers need not always debate the merits of different scales or wordings since the variations proved the overall method robust. It was important to have a questionnaire that covered all the issues, users who had experience, and activities that represented the operational environment. It was also valuable to have at least one comparison item to which the volunteer could compare to the product being tested. While not every test reported above included the ALICE, the user-volunteers had sufficient and recent experience so as to allow them to subjectively compare MOLLE to ALICE.

Good Features, Bad Features

In terms of the findings about the load-carrying system itself, the most interesting part of MOLLE's evolution was how certain weaknesses were identified early, were repeatedly found in subsequent tests but were never eliminated. In spite of continuous product improvements, there was one feature the users were having fundamental problems with (viz., the quick release mechanism) and the design team and program managers continued trying to make it work. The quick release mechanism was, at that time, one of the great early innovations that appeared to solve a long existing problem. Desire for a quick release existed years before this program began. However, until the first MOLLE prototype appeared on the scene, no one had been able to design a mechanism that was reliable and durable. In addition, the belt-release mechanism allowed the elimination of a second belt, which was also identified by users as a key problem with the ALICE. The early excitement of the new design gave most of the team members and management a positive sense of accomplishment and a belief that it would ultimately work, once the bugs were worked out. It was hard for all those involved to let go of the challenge to solve what appeared to be minor problems. In the end, the voice of the user, in the form of accumulated data, became loud and clear.

The other great innovation, the pouch attachment mechanism, proved highly successful from the start. This too was documented early on in the data and, perhaps, contributed to the optimism about being able to make the release mechanism more reliable. It was the persistence of results that allowed better judgement to prevail. The only way the process might have been shortened, in this case, would have been if an attached belt alternative had been introduced sooner. But that, alas, is hindsight speaking.

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Appendix

HUMAN FACTOR EQUIPMENT QUESTIONNAIRE (Condensed)
Load System

User: ________________________________ Date: __________________

Rate equipment/system on each factor listed below:
Circle each item SEPARATELY. DO NOT OMIT ANY ITEMS.
(? = N/A or Can't Say)

	Very "Bad"			Neither |			Very "Good"	
1. Fit of Load-Bearing Vest (LBV)	-3	-2	-1	0	+1	+2	+3	?
2. Fit of RUCK & FRAME?	-3	-2	-1	0	+1	+2	+3	?
3. How COMFORTABLE was system?	-3	-2	-1	0	+1	+2	+3	?
4. BALANCE when loaded?	-3	-2	-1	0	+1	+2	+3	?
5. How STABLE while moving?	-3	-2	-1	0	+1	+2	+3	?
6. How easy to ADJUST?	-3	-2	-1	0	+1	+2	+3	?
7. Ability to PUT-ON QUICKLY	-3	-2	-1	0	+1	+2	+3	?
8. Ability to TAKE-OFF QUICKLY	-3	-2	-1	0	+1	+2	+3	?
9. How EASY-TO-USE w. gloves?	-3	-2	-1	0	+1	+2	+3	?
10. Ability BEND BODY wearing	-3	-2	-1	0	+1	+2	+3	?
11. Ability to BEND/MOVE ARMS	-3	-2	-1	0	+1	+2	+3	?
12. Ability to REACH pockets	-3	-2	-1	0	+1	+2	+3	?
13. Ability to WALK wearing	-3	-2	-1	0	+1	+2	+3	?
14. Ability to RUN wearing	-3	-2	-1	0	+1	+2	+3	?
15. Feel on SHOULDERS	-3	-2	-1	0	+1	+2	+3	?
16. Feel on BACK	-3	-2	-1	0	+1	+2	+3	?
17. Feel on HIPS	-3	-2	-1	0	+1	+2	+3	?
18. QUIETNESS of Load System	-3	-2	-1	0	+1	+2	+3	?
19. Design of CLOSURES/SNAPS	-3	-2	-1	0	+1	+2	+3	?
20. Design of POCKETS/POUCHES	-3	-2	-1	0	+1	+2	+3	?
21. Design of FRAME-LOCK	-3	-2	-1	0	+1	+2	+3	?
22. Design of BELT System	-3	-2	-1	0	+1	+2	+3	?
23. Compatibility w. BODY ARMOR	-3	-2	-1	0	+1	+2	+3	?
24. Ability to SHOULDER WEAPON	-3	-2	-1	0	+1	+2	+3	?
25. Ability FIRE WEAPON PRONE	-3	-2	-1	0	+1	+2	+3	?
26. Ability to LOW CRAWL wearing	-3	-2	-1	0	+1	+2	+3	?
27. Ability to CRAWL UNDER things	-3	-2	-1	0	+1	+2	+3	?
28. Ability to CLIMB OVER things	-3	-2	-1	0	+1	+2	+3	?
29. WEIGHT of System Empty	-3	-2	-1	0	+1	+2	+3	?
30. Ability RECONFIGURE missions	-3	-2	-1	0	+1	+2	+3	?
31. DURABLE/STRENGTH of system	-3	-2	-1	0	+1	+2	+3	?
32. Ability to HOLD MISSION ITEMS	-3	-2	-1	0	+1	+2	+3	?
33. STABILITY of Pouches	-3	-2	-1	0	+1	+2	+3	?
34. Ease of OPENING UP to vent	-3	-2	-1	0	+1	+2	+3	?
35. Design for GROUND ops	-3	-2	-1	0	+1	+2	+3	?
36. Design for AIRBORNE ops	-3	-2	-1	0	+1	+2	+3	?
37. Design for COLD weather	-3	-2	-1	0	+1	+2	+3	?
38. Design for HOT weather	-3	-2	-1	0	+1	+2	+3	?
39. Design for JUNGLES	-3	-2	-1	0	+1	+2	+3	?
40. Design for DESERTS	-3	-2	-1	0	+1	+2	+3	?
41. Design for CLEANING	-3	-2	-1	0	+1	+2	+3	?
42. Design for REPAIR	-3	-2	-1	0	+1	+2	+3	?
43. Design for STORING	-3	-2	-1	0	+1	+2	+3	?
44. Compared to OTHER LBE Systems	-3	-2	-1	0	+1	+2	+3	?

45. Comments:

Human Factors Engineering in the Development of a New Load Carriage System for the Canadian Forces

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Summary

Human Factors Engineering (HFE) is contributing significantly to Canadian soldier protective clothing and personal equipment development and acquisition. From the conduct of user surveys and studies of baseline system performance, through the execution of controlled trials with representative users in the laboratory or the field, HFE is now impacting on virtually every stage of the Canadian soldier system development and acquisition cycle. This is especially the case for the development and acquisition of a new load carriage system for the Canadian Forces, under the auspices of the ‘Clothe the Soldier” project. The integrated design team, led by DCIEM, involved experts in HFE, biomechanics and load carriage system design from the Department of National Defence, academia and industry. The team followed a user-centered iterative design and evaluation process to rapidly develop an integrated load carriage system that will meet the range of needs of Canadian soldiers. The system includes a tactical vest, a large rucksack and small pack system, each with removable and interchangeable storage pouches making it adaptable or configurable according to mission, environment, and individual needs. The paper will present an overview of the Human Factors systems design approach used to identify and validate user requirements, and will highlight some of the many lab and field evaluations and analyses used to make design and procurement decisions.

Introduction

Human Factors Engineering (HFE) input throughout the military equipment development and acquisition process has been invaluable for the cost-effective procurement and integration of military systems that will enhance operator performance as well as operational capabilities. HFE applies knowledge of human capabilities, limitations and needs to the system design process and strives for systems that are easier to learn, use and maintain. HFE ensures that systems are compatible with the full range of users, their equipment and tasks, that foster wider user acceptance, and that improve operator and system safety, reliability and efficiency.

Human Factors specialists in Canada are providing scientific support throughout the development, acquisition and life cycle management process (as shown at Figure 1) for many items of soldier clothing and equipment. HFE support has helped to maintain a user-centered focus and has included the following activities:

- the conduct of surveys of user characteristics or user opinion and conduct of baseline system performance studies to help define and validate user requirements;
- the development and validation of performance-based specifications for the acquisition of commercially-available products or new products that can be developed for the military by industry;

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- participation as members of integrated development teams to provide design input based on user needs and knowledge of human capabilities and limitations, and to test product iterations with users in the laboratory and field environments in order to validate that user requirements are being met and that soldier safety, performance and satisfaction are being improved with each design iteration;
- the conduct of highly controlled human-centered bid evaluation trials to ensure compliance with human-based performance specifications and user requirements and to ensure that there is empirical evidence of compliance or non-compliance with performance-based specifications;
- conduct of anthropometric surveys to characterize the user population, and product fitting trials to determine item sizing (who fits which size) and size tarriffing (how many of each size should be procured);
- development of user training materials to assist with effective system implementation; and
- continuous monitoring of system performance and user satisfaction post-implementation (to ensure the success of training efforts, to monitor any changes in user requirements and to collect evidence of user requirements for future replacement items)

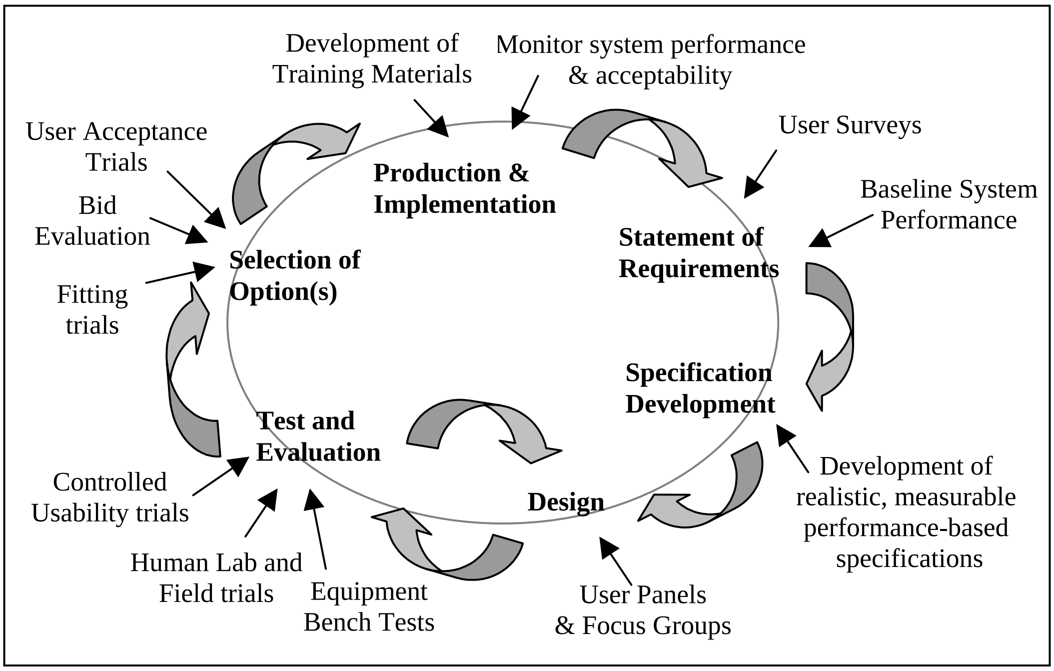

Figure 1. HFE Input throughout DND’s materiel development and acquisition Cycle (actual process highly iterative)

A Human Factors systems approach may be characterized by the following:

- user-centered design philosophy
- multi-disciplinary team
- rapid prototyping
- iterative design and testing cycle

Soldier involvement throughout the iterative development and testing process is considered essential to achieve the following: identification of detailed deficiencies about the in-service product; determination of user and mission requirements for the new system; development of test and evaluation criteria and methods that will best assess system suitability in terms of user requirements; concept validation; identification of the positive and negative aspects of each concept or design iteration; solicitation of ideas for product improvement; validation that the product will support performance, comfort and mission effectiveness when users perform tasks under the range of operational conditions; and perhaps most importantly, user acceptance and buy-in.

Human Factors Engineering has made important contributions to the development of a new load carriage system for the Canadian Forces including many of the activities mentioned above. This report will present the rationale for a new load carriage system, the design philosophy and approach taken by the team responsible for the system's design, and will highlight the range of Human Factors activities undertaken throughout the development process. The new load carriage system (comprising a Tactical Vest [TV], rucksack and small pack system) will be described and recommendations for the successful fielding of the system will be given.

Load Carriage Design Team Approach

DCIEM was tasked by the Clothe the Soldier (CTS) project[1] to validate the user requirements and lead the development of a new load carriage system, due to prior successes with HFE intervention in other projects, and expertise gained through their load carriage biomechanics research and development programme (described in Bossi et al, 2000). An integrated multidisciplinary product development team was formed, combining expertise from the Department of National Defence (DND), industry and academia. The team comprised DCIEM, as overall design team leader, two experienced vest and pack design/manufacturing firms (Pacific Safety Products & Ostrom Outdoors), an HF consultancy with over a decade of experience in the soldier systems domain (HumanSystems Inc.), as well as a team of load carriage biomechanists (Ergonomics Research Group, Queen's University). DND participation on the design team also included staff from the Directorate of Land Requirements (DLR) and the Directorate of Soldier Systems Program Management (DSSPM).

Figure 2 depicts the multidisciplinary and user-centered iterative process used to develop the new load carriage system. The extent of user involvement is quite evident. Their participation ranged from participation in focus group assessments of allied and commercial load carriage systems and early prototypes through to intensive controlled user trials in the field.

It may also be seen from Figure 2 that lab-based biomechanical assessments also contributed throughout the design process. These assessments made use of a new suite of objective measurement tools that are described in several separate papers in these proceedings (Bossi et al, 2000; Reid et al, 2000a; Reid & Whiteside, 2000b; Stevenson et al, 2000). They permitted efficient and quantitative assessment of a range of vest and pack design iterations, both for feature as well as overall system performance. Specific design questions that were answered using these tools will be highlighted throughout the paper.

Sequence of Development Activities

The same sequence of development activities was followed for each component of the load carriage system. As shown in Figure 2, the first step involved a literature and state-of-the art review by the HF, biomechanics and designer members of the team to identify the issues and technologies relevant to the system. User requirements were drafted by the staff of the Directorate of Land Requirements and validated by the HF and design members of the team through surveys, interviews, focus groups and/or tests with representative users. The in-service systems plus a range of commercial and allied military load carriage systems and components were acquired and reviewed with users to identify deficiencies, user needs and preferences for features and functionality, and to determine methods and criteria that would adequately test functionality and performance requirements. The designers were then allowed to translate the findings into prototype designs. In every case, at least two opposing design alternatives were fabricated, to ensure that users would be exposed to the range of available options and to control for design team bias. The prototypes would then be tested in two ways: through user-based testing by the HF team members, and quantitative biomechanical testing by the Ergonomics Research Group at Queen's University.

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[1] The Clothe the Soldier (CTS) project is an omnibus capital project to acquire 24 items of improved and compatible clothing and equipment for Canadian soldiers, including a new load carriage system.

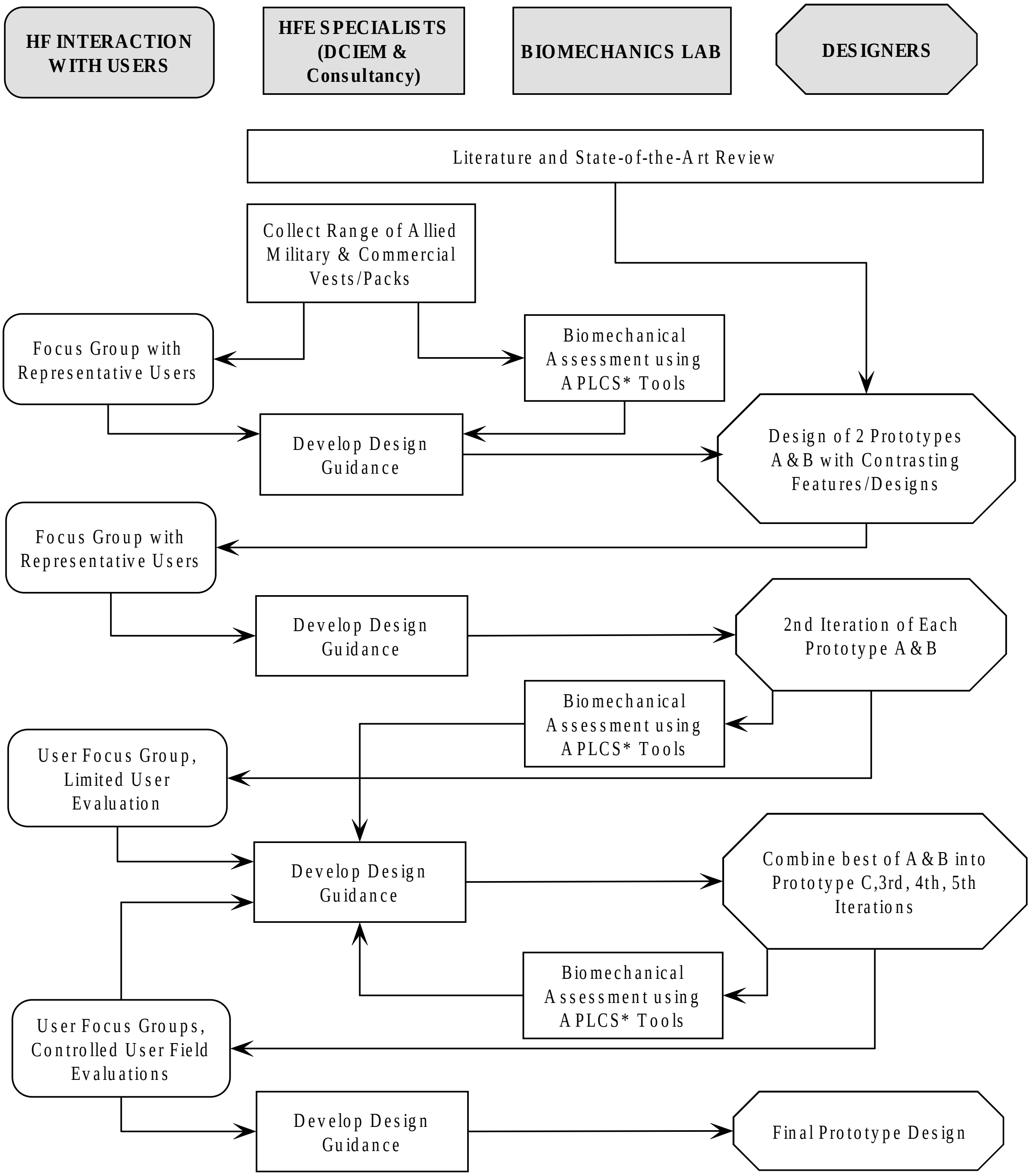

Figure 2. Integrated Load Carriage System Development Process
(*APLCS = Advanced Personal Load Carriage System Evaluation Tools)

User testing was progressive, starting with focus group discussions and limited testing of early prototypes through to highly controlled usability evaluations in the field. Typically, these field evaluations involved representative soldier subjects performing a range of critical tasks, from static/dry compatibility test stands (to examine such factors as fit, range of motion, physical compatibility with other equipment), through to assessment of performance during increasingly complex but realistic soldier tasks (from performance on marches, obstacle courses, or weapon firing ranges, through to vehicle ingress/egress/operation tasks and group level tasks such as house clearing and battlefield assault). Measures of performance included objective task performance (e.g., task timings) as well as subjective opinion and subjective ratings of acceptability collected via questionnaire and focus group discussions. Fitting trials and extended duration cross-seasonal durability and soldier acceptance trials were conducted with the more mature prototypes.

The findings from each interaction with users and every quantitative test were translated into design guidance and performance requirements by the HF and biomechanics team members. The designers were then responsible to modify the design of each prototype to address the identified shortcomings and achieve the necessary functionality and performance. Wherever possible, the team went back to the same users who had provided input for that design iteration to confirm that the functionality and performance objectives of users had been met by the design modification. The final acceptance testing involved an entirely different and larger set of soldiers to reduce the risk of bias. Although Figure 2 indicates only four iterations of the design and testing process, there have been over a dozen iterations of each component prototyped and tested in this development effort.

Statement of Requirements for a New Load Carriage System

The in-service 1982-pattern load carriage system, shown at Figure 3, is modular and includes the following components:

- Webbing, comprising a padded yoke-style shoulder harness and web belt, onto which a range of storage pouches can be attached (via clips that fit into the web belt grommets and velcro tabs that fit around the web belt) to carry the soldier’s fighting load (Fighting Order) for sustainment of up to 8 hours (essentially “bombs, bullets and water”);
- Small Field Pack (“Butt Pack”) , essentially a larger storage pouch or bag that is added to the Fighting Order, attached to the back of the web belt, enabling soldiers to carry up to 24 hours of equipment such as rain gear or extra ammunition (webbing + butt pack = Battle Order); and
- Rucksack, an external wire frame rucksack, onto which the sleeping system (housed in a compressible valise) and main storage bag can be affixed, providing up to 72 hours of sustainment load (Fighting Order + Rucksack = Marching Order).

When soldiers modify or replace their issued equipment, it is usually a good indicator of their dissatisfaction and as well as a failure in the design and procurement process. For example, many soldiers have adopted use of an unstructured small pack, originally intended for carrying the soldier’s NBC (nuclear, biological and chemical) Individual Protective Ensemble (IPE), apparently to overcome problems they were experiencing with the 82-pattern system: inadequate storage capacity in the Butt Pack; and difficulty removing or attaching the Butt Pack to the web belt, causing users to wear the Butt Pack under the Rucksack (which is incompatible as shown at Figure 3). When fragmentation protective vests were acquired and issued to our deployed troops, problems associated with webbing incompatibility led soldiers to modify their frag vests (i.e., cut slits in the outer shell fabric) to carry items such as bayonets, magazines or field dressings. This precipitated the rapid design and urgent fielding of the Load Carriage Vest (shown at Figure 4), a two-size unstructured garment with large capacity pockets. Such soldier adaptation is an indication that the range of user requirements was not adequately considered when the 82-pattern system was developed and tested.

Figure 3. In-service 1982-pattern load carriage system comprising Webbing (top left)and an external frame Rucksack. Note the incompatibility between Butt Pack and Rucksack in photo on right.

Figure 4. Load Carriage Vest rapidly designed and fielded to overcome problems of incompatibility between the webbing and fragmentation protective vest

Soldier dissatisfaction with the 82-pattern load carriage system has been widespread. In 1992 and 1993, a questionnaire-based mail-out survey of Canadian soldiers (n=487) on UN missions in the Former Republic of Yugoslavia revealed the extent of user dissatisfaction (Shek et al, 1996). Soldiers were asked to rate the acceptability of a range of clothing and equipment items, including the 82-pattern load carriage system. They were also asked to list their 3 'best' and 3 'worst' items of kit. Respondents (n=487) were representative of combat troops, with 64% at the Corporal/Private rank, and 71% being infantry. Half of respondents (n=280) rated the 1982-pattern rucksack as unacceptable and this item ranked at the top of the ‘worst kit’ list. The 82-pattern webbing was rated only slightly more favourably, ranking eighth on the ‘worst kit’ list. Interestingly, the IPE bag, which soldiers were using to overcome deficiencies in the 82-pattern system, was ranked seventh among their ‘best’ items of kit.

During the development of the Army Clothing and Equipment Survey System (ACCESS), over 700 personnel were surveyed using a range of survey strategies and techniques. Considerable dissatisfaction with the 82-pattern load carriage system was identified with each survey (Tack & Gaughan, 1997a & 1997b; Kumagai & Tack, 1999). Specific problem areas were identified: incompatibility between the webbing and rucksack at both the shoulders and hips; unsatisfactory load order integration (difficulty transitioning from fighting to battle to marching order); poor load distribution; discomfort and circulation problems (rucksack palsy); insufficient load carriage capacity; difficulty changing modular webbing components; poor fit, especially for individuals with shorter torsos; and poor durability (rucksack frame and webbing components).

System Design Goals & Constraints

The team’s overall system design goals for the new load carriage system included the following:

- effective load order integration, enabling easy and rapid transition from Fighting to Battle to Marching Order
- modularity and mission configurability
- enhanced task performance
- good fit and adjustability to accommodate not only the range of soldier sizes, but for a given soldier, the range of clothing conditions
- physical and thermal comfort
- compatibility with soldier clothing, equipment, weapons, communications gear, vehicles and tasks
- high degree of user acceptance (so that it would be the load carriage system of choice for military and recreational activities)

Regular design review meetings, user involvement and the multi-disciplinary nature of the team ensured a focus on these design goals. Participation in CTS project review meetings also ensured that the higher-level project goals, constraints and issues were addressed. These included: speedy development to achieve rapid fielding, affordability of the design effort and eventual product, and due consideration of life cycle management costs of the system. The team was asked to develop the Tactical Vest (TV) as a priority and then focus on the integrated small pack system and rucksack. The involvement of the pack designer throughout the TV development process and the commitment of the whole team ensured to a systems approach ensured effective integration of all load carriage system components.

Human Factors Engineering in the Development of the TV

Statement of Requirements Phase. Previously mentioned user surveys (Kumagai & Tack, 1999; Shek et al, 1996; Tack & Gaughan, 1997a & 1997b) highlighted the following problems with the 82-pattern webbing: poor load order integration (difficulty transitioning from Fighting through to Battle and Marching Order), poor compatibility with the rucksack at hips and shoulders (competing hip belts and shoulder straps), difficulty changing modular pouches, and poor durability of the pouch attachment mechanism.

The interim solution to some of the incompatibility problems, the LCV (shown at Figure 4), was rated by ten percent of respondents to an ACCESS newspaper insert survey (n=285) as one of their best items of issued kit (Kumagai & Tack, 1999). Although this number seems unimpressive, very few soldiers would have had experience with the LCV at the time of the survey.

Although the LCV was highly regarded by the troops who had worn it, several concerns with its design led to the decision to develop a replacement vest. These included: vest length (the vest came down to the level of the hips) that precludes effective integration with the hip belt of a new rucksack; excessive insulation due to the material chosen for the vest, its loose fit, and its coverage on the body; excessive stowage capacity, causing troops to overload themselves; and poor load stability, due to its loose fit, limited number of sizes (only 2) and lack of sufficient adjustability (drawstring at the waist only).

Specification Development Phase. The TV design criteria developed by the team included the following (in no particular order): enhance task performance; distribute weight more effectively; minimize load shifting; minimize heat load, reduce bulk; improve the sizing range; allow for customized fit adjustment; support mission and personal preference configurability; integrate well with the rest of the load carriage system; be compatible with other clothing and equipment worn and used by soldiers; incorporate usable closures; be durable and field repairable; and accommodate and ensure accessibility to high priority items. Management criteria included the following requirements: a rapid but affordable design; accommodation and compatibility with the future small pack system and rucksack; compliance with Army doctrine and tactics with respect to load item priorities; and reduced logistics support once in-service.

A user panel of 15 Master Corporal/Sergeants (representing combat arms, combat support arms and combat service support occupations) was raised to support the initial design efforts. Initial focus groups reviewed the in-service webbing and LCV as well as several allied vests. Advantages and disadvantages were highlighted and vest functionality and feature requirements were identified. The pros and cons associated with the 82-pattern webbing and LCV are shown at Table 1.

Table 1. Review of in-service fighting order options by soldier user panel

82-Pattern Webbing		**Load Carriage Vest**	
PROS	CONS	PROS	CONS
Ventilation	Hip bulk	Weight distribution	Fit
Mission/personal configurability	Yoke discomfort	Compatibility with frag vest	Ventilation
	Durability problems	Load volume	Limited modularity
	Poor weight distribution	Pouch durability	Load volume
	Compatibility with frag vest/rucksack		Rucksack compatibility
	Vehicle compatibility		Select features

A rapid prototyping vest was used for determining load placement preferences. This vest comprised a fragmentation vest as well as a number of separate pockets for each of the high priority items of kit (magazines, grenades, water canteens). Users were asked to place the filled pockets in their preferred location on the outer surface of the frag vest (via hook and pile on vest/pockets) and go through a range of typical tasks in order to identify the optimal load placement. A sampling of rucksacks was available for this testing to help ensure that load placement would not interfere with the future rucksack suspension system.

Design Phase. Two opposing vest designs were then developed and tested by the user panel in an iterative fashion: the Modular TV, and the Fixed TV, named for the nature of pocket attachment. Each took the advantages and tried to overcome the disadvantages of the 82-pattern webbing and LCV respectively, as shown schematically in Figure 6.

Both the Modular and Fixed vests had similar construction (mesh and webbing materials), body coverage (cut short to avoid future rucksack hip belt) and pocket placement options. Both had C7 rifle magazines and HE grenade pouches permanently fixed across the chest (no other options were considered suitable by the user panel). However, they differed predominantly in that the Modular TV had removable pouches for the water canteen, C9 ammunition drum and ancillary kit pouches. Additionally, a number of features were varied across the two vest prototypes: vest closure and fit adjustability mechanisms; material options (both used mesh of varying stiffness and weave construction; different padding and width of shoulder harness);

pocket designs (attachment, material, size, closures, hold-open device, stiffness, etc); and the integration of other equipment items (bayonet, flashlight, smoke grenades, web-belt, etc).

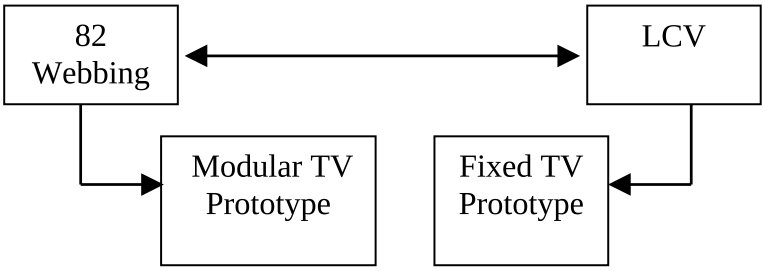

Figure 6. TV Design Options

Many different magazine pockets were prototyped and tested (see Figure 7) to ensure that users would have quick and easy access to their magazines in any firing position, and also be able to return empty magazines to the pockets single-handed. A stiffner, incorporated into the front surface of the pocket, facilitated the latter. User testing confirmed that the use of side-release buckles plus a stiffener in the front panel of the pocket permitted the fastest times for magazine removal and replacement, in both bare-handed and gloved conditions.

Figure 7. Rapid prototyping vest (top centre) and range of magazine pocket designs and features evaluated for accessibility

Test and Evaluation Phase. During the iterative development of the TV, quantitative biomechanical testing confirmed which pocket design and attachment mechanisms would provide the best load stability, and which shoulder strap designs (varied width, padding versus flat webbing) would minimize skin contact pressures and be most compatible under the future rucksack (Bryant et al, 1997a; Reid et al, 1999a).

An intensive highly controlled usability evaluation was conducted in August of 1997 to assess the two TV prototypes against the two in-service options. Two groups of sixteen soldiers participated in the five-day field trial at CFB Petawawa. All subjects wore both TV prototypes and one of the 82-pattern webbing or LCV in an incomplete block repeated measures study design. Standardized testing occurred across a range of test stands and activities: three 5 km marches, an obstacle course, weapons firing, grenade throw, battle tasks (section attacks, house-clearing) and compatibility test stands (to test compatibility with the range of clothing conditions, radios, personal and crew-served weapons, vehicles and both in-service and allied rucksacks, since the CTS pack was yet to be designed). In addition to performance measures, subjects gave ratings of acceptability for a range of test criteria after each activity and in an exit questionnaire on the last day of the trial. The Modular TV was preferred over all other options for ease of adjustment, packing, load item capacity, ease of access to items, compatibility with personal weapons and equipment, mission configurability and battle task performance. Both the Modular and Fixed TV conditions were preferred over the in-service options for ease of donning/doffing, compatibility with shoulder-fired weapons, rucksack compatibility, physical comfort, ease of movement, load balance, load stability and casualty extraction. The 82-pattern webbing was preferred over all other options only for thermal comfort.

Since thermal comfort was a concern in the decision to develop a vest, the results will be highlighted here. After each 5 km march, subjects were given a thermal comfort questionnaire. The questionnaire depicted the front and back of the body (predominantly torso) and a rating scale. Subjects were asked to indicate areas of thermal discomfort by circling the area and then entering their thermal comfort rating for that area. Table 2 provides a summary of results across the trial conditions.

Table 2. Percentage of subjects who indicated a thermal comfort rating and the mean of their thermal comfort ratings by body zone across the four Fighting Order conditions. Shaded cells indicate when >50% of subjects reported discomfort (or >70% if bold).

	82-PATTERN		IN-SERVICE LCV		TV FIXED		TV MODULAR	
ZONE	%	Mean Rating*	%	Mean Rating*	%	Mean Rating*	%	Mean Rating*
Shoulders	**80**	3.4	64	4.1	63	3.4	50	3.7
Sternum	33	3.5	**71**	3.8	37	3.2	61	2.2
Stomach	7	3.0	64	4.0	37	4.0	54	3.4
Underarm (front)	**		7	2.0	33	3.3	29	3.8
Waist	13	4.5	21	3.7	11	4.3	4	5.0
Upper Back	**73**	3.5	64	4.1	59	3.3	61	3.1
Middle Back	33	3.8	**93**	4.2	67	3.4	**71**	3.5
Underarm (rear)	**		7	2.0	22	3.8	18	3.6
Lower Back	20	3.7	36	3.6	22	3.5	22	3.7

1=neutral, 2=slightly warm, 3=warm, 4=hot, 5=very hot

** webbing does not cover these areas

It can be seen from Table 2 that the in-service LCV had among the highest thermal discomfort ratings and the highest number of subjects reporting thermal discomfort. Not surprisingly, all three vests solicited more thermal discomfort feedback than the 82-pattern webbing, although the heat build-up under the 82 webbing shoulder harness and yoke are apparent.

At the end of the usability trial, a large exit focus group queried participants about their final overall preferences. Table 3 indicates the results when soldiers were asked to indicate which of the four Fighting Order conditions they would want to walk away with that day, and which they would prefer, if some minor modifications (identified during the trial) were made. Eighty-seven percent were happiest with the Modular TV as designed, and with the minor modifications suggested, that figure was raised to 94%. Surprisingly, none of the soldiers preferred the LCV and a few were happiest with the 82-pattern webbing. Their reasons related to thermal comfort and mission/personal configurability.

Table 3. Final user preferences by Fighting Order condition

Fighting Order Condition:	Acceptable As Is		Acceptable with Mods	
	#	%	#	%
Modular TV	27	87%	29	94%
Fixed TV	1	3%	1	3%
LCV				
82 Pattern Webbing	3	10%	1	3%

Since that usability trial was conducted, a number of design modifications to the TV have been incorporated and validated with users. These came about as a result of this trial and the many sessions with users during the development of the remainder of the load carriage system. Every test session for the rucksack and small pack system naturally included the TV, since it is an underlying layer.

Figure 8 shows a drawing of a near-to-final TV design. It is constructed of mesh fabric, 500 denier Cordura pocket material and a range of webbing materials. It is available in two sizes and accommodates the range of soldier clothing conditions (from combat clothing alone through to the full winter ensemble including fragmentation vest). Adjustability is achieved circumferentially via three pairs of webbing straps with metal ladderlock buckles. Vertical adjustment is available at the shoulder, using hook and pile. To tighten the load immediately prior to an engagement, the soldier can use the load lifter webbing straps on the front of the vest. The vest incorporates a casualty recovery strap across the top of the back in case an unconscious soldier has to be dragged or lifted out of a hazardous situation. ‘Daisy-chain’ webbing on the back of the vest allows for the attachment of equipment or modular components of the small pack system (to be described). Four C7 magazine pockets, two HE grenade pockets and two ancillary stowage pockets are affixed across the front of the vest. The innermost magazine pockets include stowage for a mini-mag light (inner right) and a whistle (inner left). Two each of modular water canteen and C9 ammunition drum pockets (left and right) are available with each vest. Each of these pockets includes stowage for a smoke grenade. A bayonet can be housed on the front zipper flap with the blade in the up or down position. Inside the vest is a mesh pocket for stowage of maps. Wide flat webbing was chosen to replace the padded shoulder straps in order to minimize pressure points and optimize integration with the new pack system (Reid et al, 1999a).

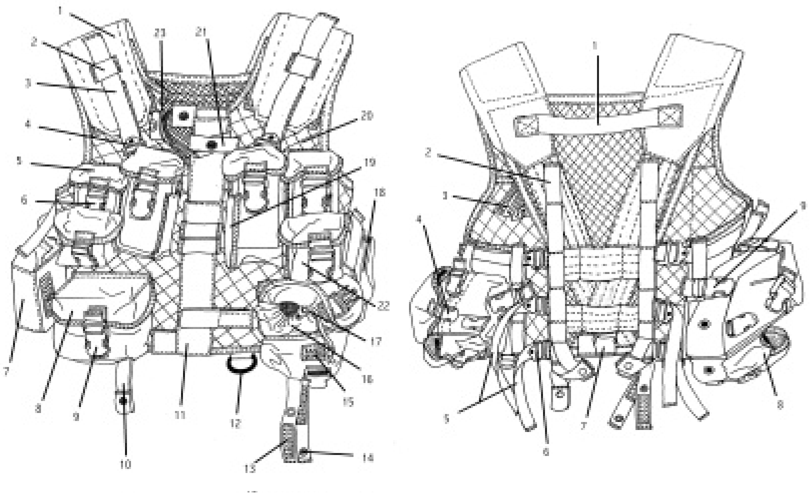

Figure 8. Near-to-final TV Design (front and back)[2]

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[2] Drawings used in this paper were taken from questionnaires used in trials and focus groups with trial troops. Numbers and stars refer to specific parts of the item that were rated by users for functionality and durability. Starred items (seen in later drawings) were those found in user trials to require redesign or modification. These have since been modified and have been confirmed by users as acceptable.

Human Factors Engineering in the Development of the Rucksack and Small Pack System

Statement of Requirements Phase. Surveys previously mentioned (Kumagai & Tack, 1999; Shek et al, 1996; Tack & Gaughan, 1997a & 1997b) point out the extent to which Canadian soldiers were dissatisfied with the 82-pattern rucksack. Problems reported included: incompatibility with webbing; unsatisfactory load order integration; poor load distribution; discomfort (including rucksack palsy); poor fit, especially for individuals with shorter torsos; and poor durability (rucksack frame). The fact that soldiers were using the IPE bag to augment their load carriage system indicated their desire for a small pack. The design team reviewed the feedback that had already been gathered in order to refine and validate the Statement of Requirements for the new small pack system and rucksack.

Specification Development Phase. The same approach was taken for the development of the integrated small pack system and rucksack. Biomechanical testing of a range of commercial and allied military packs (Bryant et al, 1997b; Stevenson et al, 1995 & 1997) led to biomechanical design goals and test criteria. A user panel of 15-17 experienced soldiers (Master Corporals/Sergeants, predominantly infantry but also representing other combat arms and combat support trades) were involved in at least six design review focus group and testing sessions. Initial sessions reviewed in-service, commercial and allied packs to identify and prioritize functionality and feature requirements. Table 4 provides the mean ratings of importance in rank order for a range of criteria. It is interesting to note how low on the list thermal comfort scored in the criteria importance (although it is still rated as important). Together with their dissatisfaction with the external-framed 82-pattern pack, this may help to understand the overwhelming preference of the user panel for an internal framed pack design. The design team also favoured an internal frame pack, knowing that it would help keep pack centre of mass as close as possible to the body, for less back strain and better load control and stability.

Table 4. Mean pack criteria importance ratings of user panel participants.

Criteria	Mean Rating	Criteria	Mean Rating
Physical Comfort	6.5	Bulk	5.6
Fit	6.3	Pocket Closures	5.6
Balance	6.0	Capacity	5.4
Equipment Compatibility	6.0	Modularity	5.3
Range of Motion	6.0	Task Performance	5.3
Waterproofness	6.0	Clothing Compatibility	5.2
Adjustability	5.9	Stowage	5.2
Durability	5.9	Ease of Packing	5.1
Item Accessibility	5.8	Thermal Comfort	5.1
Stability	5.8	Camouflage	4.3
Weight of Pack	5.8	Appearance	3.2
Mission Configurability	5.7		

7 point scale: 1 = Unimportant, 7 = Essential

Design Phase. Two opposing internal frame pack prototypes were developed in order to expose users to the range of possibilities. The variables addressed by the opposing designs included: modular versus single bag, suspension system characteristics and features, design and integration of the small pack, design and integration of accessory pouches, mechanism and design of bag compression straps, pack lid designs, access to compartments, compartment closures, quick release options, shoulder strap shape and fit/adjustability features. The main differentiating features are shown in Table 5.

Table 5. Main features of opposing pack design concepts

Modular Packs (M)	Single Bag Packs (K)
Two separate bags (for mounting on pack frame)	Single bag pack with two separable compartments
Pack-board capability	No pack-board capability
Stiff suspension	Flexible suspension
Aluminum stays for head/helmet clearance	Plastic molded head/helmet clearance
No pack handles	Pack handles

The Modular version (Prototype M) comprised an 'internal frame' suspension system in a packboard configuration. Separate small, unstructured packs could be mounted to the pack-board to achieve mission configurability. One of the small packs could be removed from the pack-board and double duty as a small (i.e., patrol) pack if needed. The other prototype, Prototype K (actually for 'Keep it Simple') comprised an internal frame suspension system and a single large stowage bag concept, with access from the top and bottom-front of the pack to two separable compartments. Modularity was achieved with a series of add-on pouches (attached via webbing straps and ladder-lock buckles through 'daisy-chain' sewn to the outer surfaces of the pack). Integration of the small pack could be achieved in one of two ways: by attachment to the 'daisy-chain' on the outer surface of the pack (top or front) if loaded with relatively light items; or by putting the whole small pack inside the top compartment of the pack (inside the separate radio compartment) if carrying heavy items such as the combat net radio.

Consultation and increasing levels of testing took place with the representative user panel as well as parachutist instructors (to ensure 'jumpability' and robustness). Quantitative tests of the M and K-series of packs as well as a range of pack components helped to make trade-off decisions and to refine the suspension system design (Bryant et al, 1997c & 1997d; Reid et al, 1998, 1999c, 2000a, 2000b; Stevenson et al, 1998 & 2000; Whiteside et al, 1999). Both user and quantitative testing confirmed the superiority of the K-series of packs in terms of load stability, shoulder strap design, and usability. Meanwhile, the TV design was finalized and tested, both quantitatively and with users, ensuring compatibility with the rucksack suspension system. The findings from all the studies and testing on the opposing pack prototypes enabled the team to refine the design into a single integrated overall system design (with some variation on component and feature design). Figure 9 provides a drawing of the pack that would go on to further quantitative biomechanical assessment (Reid et al, 1999b; Stevenson et al, 2000) and thorough usability testing in the field.

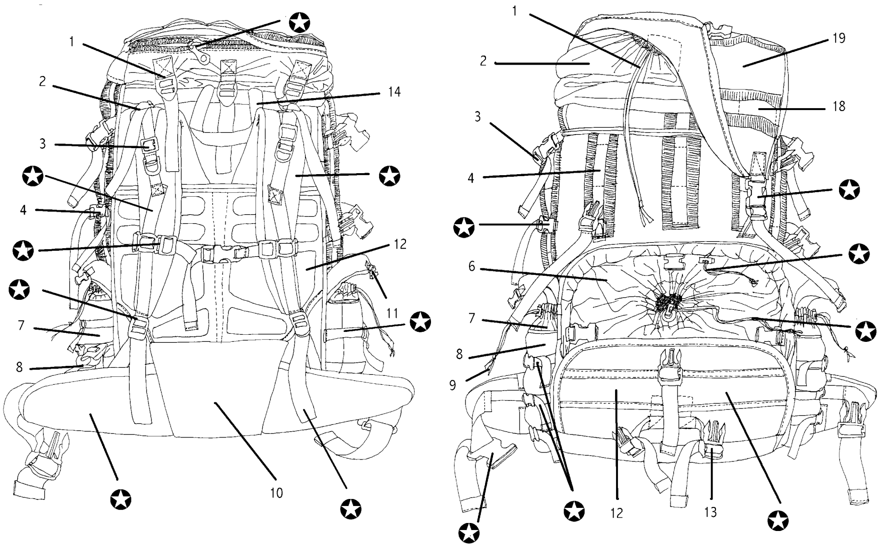

Figure 9. Near-to-final rucksack configuration.

The rucksack (85 litre capacity) incorporated a state-of-the-art suspension system (in 4 frame sizes) including: a Plastizote™ frame sheet, two aluminum stays (custom shaped), a molded lumbar/back pad with channels for air flow and heat dissipation, curved shoulder straps (in 3 sizes), molded hip belts (in 4 sizes), load lifter and hip stabilizer straps, lateral suspension stiffness rods to improve transfer of load to the hips, a sternum strap and quick release capability. The stowage concept was a single large bag design, with top and front access to one large (separable into two) compartment, plus a radio stowage compartment, floating lid, pack handles, two lower lateral fixed pockets (which have since been made removable) and all-over 'daisy chain' attachment capability.

The small pack system comprised a patrol pack (24 litre capacity) and a range of accessory pouches. The small pack (shown in Figure 10) utilized the same molded back-pad as the large rucksack and incorporated a single aluminum stay. Padded shaped shoulder straps, a sternum strap, waist belt (for load stability), load lifters (not shown in Figure 10), all-over 'daisy-chain' for attaching accessory pouches and an internal separate radio compartment characterize this system.

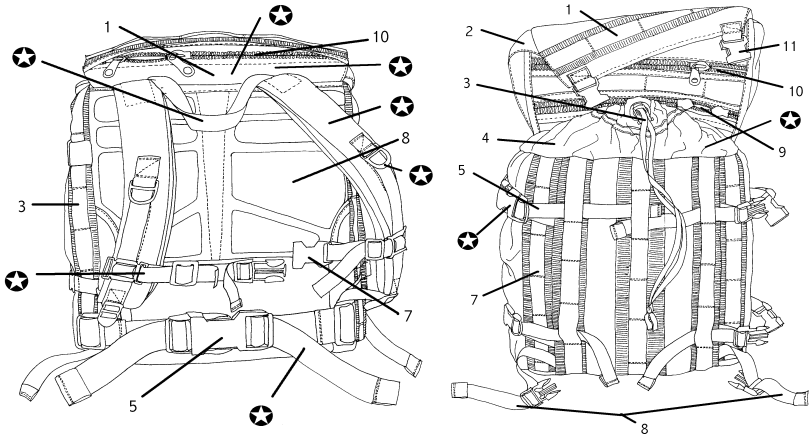

Figure 10. Near-to-final small pack design.

The accessory pouches included two (7.5 litre capacity) pouches and two small (5 litre capacity) pouches. The large accessory pouches are oblong, zippered bags that provide the option for use and wear as a standalone 'fanny-pack' around the waist. They can be attached to the back of the TV and anywhere on the outer surfaces of the small pack or rucksack (across the top, on the front or sides). The two smaller accessory pouches are essentially square, upright bags with a snow cuff and flap cover. They can also be attached to any of the three load carriage items. These additional pouches are what give the entire system its modularity. They are shown in Figure 11.

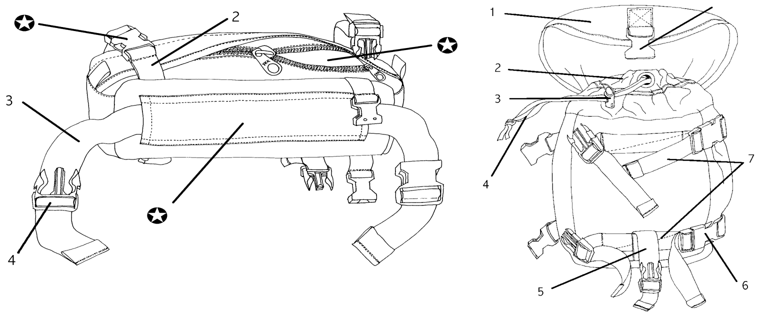

Figure 11. Accessory pouches can be added to the TV, small pack or rucksack for modularity and mission configurability

Because of the preference for a single bag design, the in-service sleeping bag valise was unsuitable for the new load carriage system (insufficient compression made it too large to fit into either the upper or lower compartment of the pack). Furthermore, users wanted a ‘waterproof’ system, to keep their sleeping system dry under conditions of stream fording or in downpours. The in-service valise does not offer this protection. A range of commercial waterproof compression sacks were acquired and tested with users to identify feature and functionality preferences. The Waterproof Compression Sack (WCS) is still undergoing development

Test and Evaluation Phase. As previously mentioned, quantitative biomechanical testing and qualitative user review of various iterations of the pack were undertaken throughout the design phase. Once the design was refined sufficiently, an intensive two-week controlled user trial of the complete load carriage system was conducted in September of 1998. Twenty-four representative subjects (67% combat arms, 33% non-combat arms; 67% men, 33% women; 3 different Brigades) evaluated the new prototype against both the in-service 82-pattern system as well as an allied system that was considered by troops (in surveys and focus groups) to be the best available. The allied system was included to control for bias against the in-service pack. Field trial test criteria for the Battle Order and Marching Order configurations of each of the three systems included: fit/adjustability, packing drills, accessibility, range of motion, clothing/ equipment/weapon compatibility, feature evaluation, individual task performance (weapon firing, obstacle courses, grenade throw), vehicle stowage, battle task performance (patrolling, fire and movement, house clearing), thermal load, physical comfort, user maintainability and overall user acceptance. There were mini-march work-ups of 2 km, then a mini-assault work-up (in Battle Order only) involving 3.5 km marches, a 1 km patrol through bush, practice section attacks and grenade throw. For each condition, each subject marched 10 km, participated in 2 km night recce patrols, went through field living conditions overnight, and, for Battle Order conditions only, conducted fire and movement, house clearing and small arms firing tasks.

The allied load carriage system was withdrawn by the third day of the trial due to severe discomfort problems. Only the results for the new prototype and the in-service system will therefore be highlighted here. Generally, the new pack was rated significantly more acceptable than the 82 (or allied) systems. The 82 system received many unacceptable ratings. The only mean unacceptable ratings given for the new pack were for the criteria of accessibility to TV C9 drum pockets or pack pockets on the march (normally, the pack would be doffed if the wearer came under attack and needed to access this ammunition). Borderline mean acceptability ratings were given for the hip belt (due to inability to achieve a tight enough fit with resultant slippage on the smaller participants), ease of donning (not surprising given the complexity of the new system), emergency doffing and TV compatibility. The TV shoulder straps were subsequently modified (from padded to flat wide webbing) to improve compatibility and the emergency doffing mechanism has since been modified for ease of use.

Figure 12 shows the mean physical comfort ratings and incidence of reporting for both the new and in-service systems following the 10 km marches. Eighty percent of participants noted discomfort on the anterior shoulders for the 82-pattern system (mean of 3.2 representing noticeable discomfort) versus 42% for the new prototype (mean of 2.4, slight to noticeable discomfort). Half of participants experienced noticeable discomfort on the front of the hips for the new pack system (Figure 12a) due to incompatibility between the hip belt and buttons on the combat trouser pockets (these have since been replaced with hook and pile closures to accommodate the new load carriage system). Physical comfort ratings for the back of the torso were reduced in severity and incidence with the new load carriage system (Figure 12b). The new design virtually eliminated reports of discomfort at the back of the neck.

Figure 13 shows thermal comfort ratings for the back of the torso. Although more thermal discomfort was experienced at the hips with the new pack (due to presence of a padded hip belt[3]), the incidence and severity of thermal discomfort ratings at the shoulders and center of the back were reduced, this despite the fact that the new system uses an internal frame.

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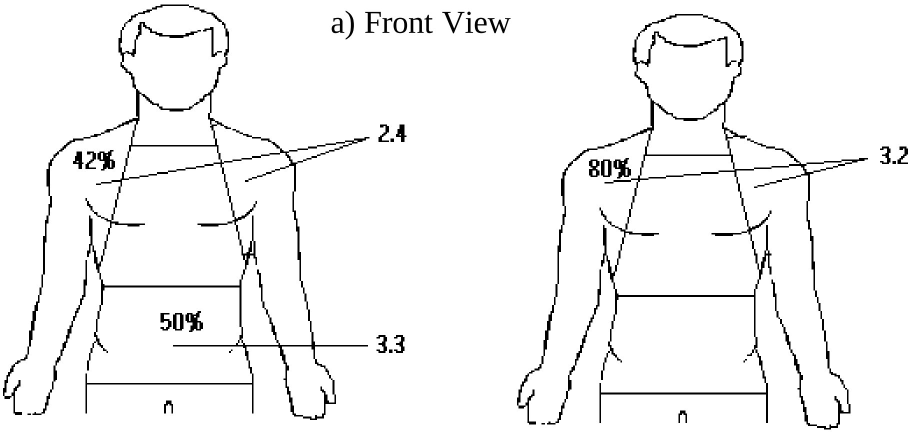
[3] The 82-pattern rucksack has only a webbing strap for hip belt. It is worn infrequently because it does not transfer load to the hips.

a) Front View



New Load Carriage System In-service 82 Pattern

b) RearView

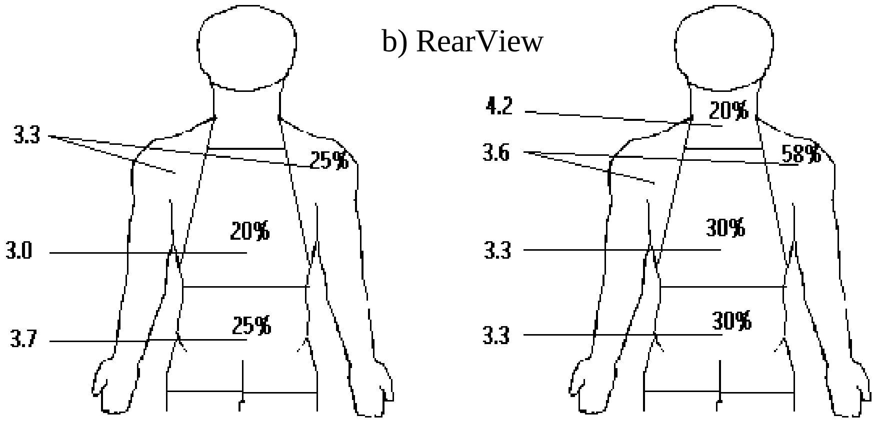


Figure 12. Physical comfort ratings, front (a) and rear (b)
(scale: 1=neutral, 2=slight discomfort, 3=noticeable discomfort, 4=pain, 5=extreme pain)

New Prototype In-Service 82-Pattern

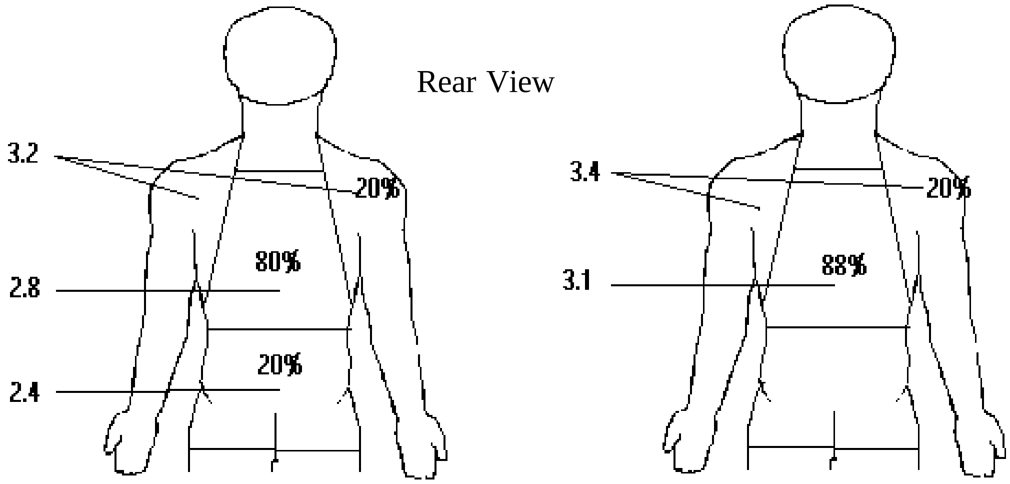


Figure 13. Thermal discomfort ratings for the back of the torso, new and in-service load carriage system
(scale: 1=neutral, 2=slightly warm, 3=warm, 4=hot, 5=very hot)

An interesting finding from testing of various battle order configurations was that users preferred using the TV with accessory pouches instead of the small pack. Cited reasons for rating the small pack less favourably included: less mobility, restricted range of motion, helmet nape clash, load instability and poor back ventilation. However, the accessory pouches provide a lot less storage capacity than the small pack so it was recognized that there would be situations when the small pack would be the option of choice. The small pack has since been modified to incorporate load lifter straps and other features to improve mobility and load stability. The trial also demonstrated the utility of the small pack as an option for sustainment loads of 24-36 hours. It has much more capacity (within the bag itself, plus accessory pouches) than any in-service option (Butt Pack, LCV or IPE bag), so troops considered the possibility that the small pack system could actually replace the large pack for mechanized troops or for operations in temperate conditions (in both cases, the load size is smaller).

Modifications were made to the load carriage system to address some of the lower-rated criteria and deficiencies identified by the user participants. Confirmatory testing sessions were conducted with a sampling of those same trial participants to ensure that the design team understood their concerns and translated them successfully into the system design. A further benefit of this strategy is that it gives confidence to soldiers that their input is being heeded.

Human Factors Support in the Selection of Options Phase

User Acceptance Trials. Several extended duration trials were conducted across a number of Canadian infantry units in order to better address the suitability of the entire load carriage system for field living conditions across each of the seasons, to gather durability data, and to obtain final user acceptance of the overall system. At the beginning of each trial, the design team would brief participants and carefully fit each with a complete load carriage system. The soldiers would then use the new system during already-scheduled training exercises (including arctic). A return visit by the design team, part-way through and at the end of the trial allowed the team to correct any misconceptions or misuses of the new system as well as collect subjective data on system usability, durability and overall user acceptance. The load carriage system was highly accepted by users. The only changes requested (now being implemented) were the enlargement of the front pack opening to facilitate the stowage and removal of the sleeping system, and redesign of the Waterproof Compression Sack (WCS), used to house the sleeping system, since the commercial variants trialled had insufficient storage capacity and durability. That design work has been completed and one final user acceptance trial of the pack and WCS is scheduled for February 2001.

Fitting Trials. A fitting trial was conducted for the complete load carriage system in June of 1999. The aims of this trial were to determine the critical anthropometric dimensions for fitting the new system, and using these, determine the range of measures for each item size. Based on these sizing ranges, it would then be possible to establish item size tariffing in relation to the 1997 Canadian Land Force anthropometry survey (Chamberland et al, 1998).

Methodology involved the fitting of loaded packs onto 193 soldiers by an expert fitter (the pack designer), having soldiers do a shake-out mini-march and then come back for fitting reassessment and adjustment of component size as required. Mean ratings of size acceptability for a range of pack components and dimensions were within 1 point about the center of a 7 point balanced interval rating scale (where 1 = too small, 4 = ideal, 7 = too big).

Analysis of correlations between anthropometric variables and the sizes of components worn by subjects identified which anthropometric variables should be used by supply personnel for determining appropriate component sizes as well as identify the range of a user sizes appropriate for a given component size (simple anthropometric measurements were used so that eventual supply personnel would be able to issue the appropriate sizes to personnel). Having the distribution of body size and shape from the recent Land Force anthropometric survey (Chamerland et al, 1998) enabled the team to develop a sizing system (an example is shown at Figure 14) as well as size tariffs (i.e., how many of each size of each component to procure for the Land Force).

Because those of shorter stature or larger waist circumference were under-represented in this fitting trial, further fitting trials are being conducted to determine the requirement for additional sizes of shoulder harness and hip belt (smaller and larger).

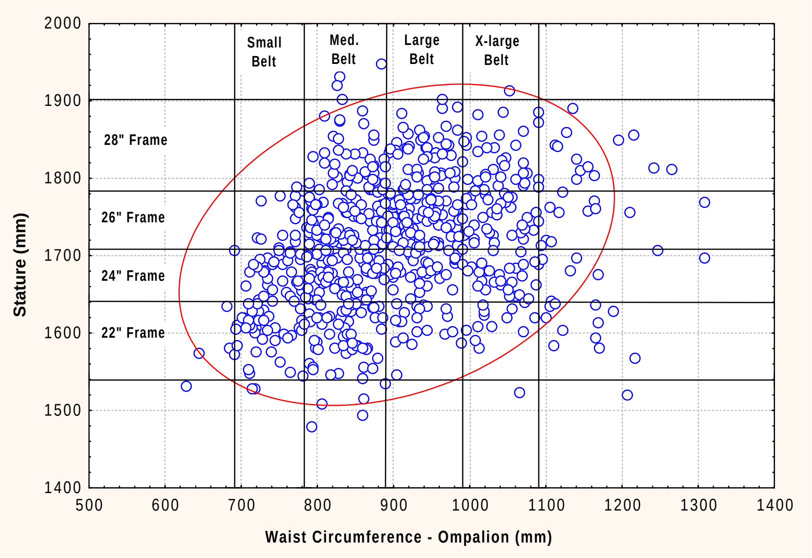


Figure 14. Sizing of pack frame and hip-belt, based on stature and waist circumference

Human Factors Support to the Implementation Phase

The complete load carriage system, as it looks today, is shown in Figure 15. The design team is currently developing a range of waterproof compression sacks for trial this winter. Further sizing and fitting evaluations are planned to determine the requirements for additional sizes of shoulder straps and hip-belts. The sizing and size tariffs will then be revised as appropriate and the technical data packages completed in preparation for the procurement process.

Figure 15. Complete Clothe the Soldier load carriage system comprising tactical vest, small pack, large rucksack, ancillary pouches and prototype waterproof compression sack.

Although the project is shifting from the development to the procurement and implementation phases, a number of HF support activities have been recommended. First and foremost, because of the complexity of system fitting, adjustability and configurability, the design team strongly advocated the development and implementation of effective training strategies, not only for the eventual soldiers who will use the system, but also for those responsible for training and issuing the system. The design team is currently developing material for effective user manuals, based upon their study of skills and knowledge retention by users involved in extended duration trials. But user manuals or videotapes are not likely to be sufficient. A ‘tiger team’ approach has been recommended whereby a team of skilled and knowledgeable staff visit major formations and units to properly ‘train the trainers’ until basic military courses offer the training in their curriculum.

The design team advocated the development and implementation of some fitting aids, because appropriate fitting of the new pack is essential to system comfort and acceptability, because it is such a complex system, and because supply staff have limited training or the time for careful body measurement. DCIEM is developing (Meunier et al, 1999) a low-cost Intelligent Clothing and Equipment Sizing System (ICESS) that can quickly capture an individual’s major body dimensions (using 2D digital cameras and specialized software) and then indicate the appropriate size of clothing or equipment that should be issued to that individual (assuming a fit/sizing trial has confirmed the sizing for that item, as will be the case for the load carriage system). Such a system, if installed in future at major clothing supply centers, would ensure the correct allocation of load carriage system components. In the shorter term, the designer is developing a fitting jig that will aid supply technicians and users in determining the most appropriate size of pack frame, shoulder strap and hip-belt for their body dimensions. This tool will be tested and validated during upcoming fitting trials.

The monitoring of user satisfaction with the delivered product post-implementation via surveys or other means is also important. Not only will it permit a validation of user acceptance using an HFE development approach, it will also identify and permit the correction of any deficiencies that may arise due to: changes in doctrine, tactics and procedures (i.e., change in load lists); changes in mission environments; changes to other components of the soldier system (i.e., modified frag vest); or any misuses or abuses that arise due to ignorance about the system.

Finally, it might be prudent to conduct studies of the thermal strain associated with wearing the tactical vest, with and without fragmentation protection, to better understand the impact of replacing webbing with the tactical vest under hot conditions and so that appropriate guidance to commanders can be developed.

Conclusions

A Human Factors user-centered systems design approach was adopted by a multi-disciplinary team to develop a state-of-the-art load carriage system for the Canadian Forces. Every effort was made to ensure that the new system would meet the range of user needs and preferences. Virtually all design decisions were supported by scientific evidence, arising either from carefully controlled user evaluations or objective biomechanical assessment. User involvement throughout the development process has given a host of benefits including: increased user acceptance, product credibility (with users, designers, procurement staff and project decision-makers alike), product and soldier system effectiveness, a reduction of risk, and economy (of sizing, mission/task flexibility, feature utility, etc.).

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Material Choices for Good Load Carriage Design

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Summary

The paper discusses the selection of fabrics, webbing, tapes, sewing threads and the issues that surround their choice in the military scenario. How infrared signature is achieved on synthetic materials, so that service personnel are hidden from night sights, is explained. A weldable material has been identified in the UK offering the opportunity to produce waterproof rucksacks. The choice of interface materials to the body is discussed and the new favoured double needle bar spacer fabric with its advantages on heat stress and load distribution capabilities is compared to the established plastic foams. The selection of buckles and the way to improve their robustness is shown. The age-old argument of internal frame versus external frame is debated.

Fabric choices

In the UK there have been two obvious possible choices of fabric for load carriage systems, these are:

- Coated polyurethane on1100 d/tex textured nylon; and
- Coated polyurethane on 560 d/tex textured nylon

The 1100d/tex textured nylon was chosen because the 560d/tex displayed unacceptable abrasion resistance in the field. More recently a third contender has appeared in the form of coated polyurethane on 770 d/tex textured nylon.

The properties follow the following rules: the higher the d/tex the higher the yarn diameter and the higher the fabric tensile strength; the lower the d/tex the lower the yarn diameter and the lower the equipment weight.

The abrasion needs to be assessed by field trial. Many laboratory tests have been developed for abrasion testing, but unfortunately none give reliable results in comparison to what happens in the field. This is because stiffer/stronger fabrics tend to lead with their chins thereby sustaining more damage.

Sewing thread

Experience in the UK has clearly shown that a metric count of at least 25 (120d/tex) is necessary for military rucksacks. 50 (68d/tex) metric was favoured for commercial manufacture, but this lead to catastrophic seam failures when used in the military arena. Metric measure is defined in an British Standard (BS 4134:1990),but a simple understanding is that the larger the metric count the thinner and weaker the yarn.

Weldable fabrics

A heat/H.F.(high frequency) weldable version of the 560d/tex material exists in the UK. This opens up the possibilities of producing a fully waterproof rucksack and by incorporating a CW (chemical warfare) agent protective film, chemical protection to the contents. A totally waterproof rucksack has been produced using

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this technology in our workshop. Fabrication using welding is more expensive than sewing and because of the welding tools item shape is more restrictive.

Colour

The choice of colour is very simple for the military and it is either olive drab or disruptive pattern print (DPM). The difficulty lies with achieving the correct infra red reflectance (IRR). In the case of the olive drab this is achieved by incorporating selected pigments in the PU coating. In the case of the DPM, pigment printing with selected pigments will achieve the correct result. Conventional printing with acid dyes will produce better colour fastness, but will not give the desired IRR result. The colour fastness of the pigment print was checked by repeated trialling of the kit around an assault course where it was established that the fabric wore out before the print faded.

Buckles And Fittings

Buckles can be manufactured from metal or plastic. In common with other NATO nations the UK chose the more cost effective option of plastic. The choice of plastic is critical. The UK chose Acetyl for the ladderlock buckles and replaced nylon by Delrin500T for the side release buckles. The nylon side release buckles were initially trialled, but gave too many failures.

New generations of buckles which are lighter and stronger are currently available from ITW Nexus. Although these buckles are fully compatible in their range, they are not compatible with the existing buckles.

Webbings and Tapes

The webbing and the buckles need to be fully compatible so that easy run through and lock is achieved. Nylon webbing is currently the choice of UK MoD because of its better abrasion resistance, although it suffers more from creep than polyester. IRR is built into the webbing and tapes by the incorporation of a fine d/tex black spun coloured yarn in the weft. If the correct proportion of black spun coloured yarns to green yarns are used, the NATO specification for IRR is consistently achieved.

Interface Materials

Outlined below are a number of choices for interface materials:

- Polyethylene closed cell.
- Open cell foams
- Foam combinations
- PU (Polyurethane) foams
- Phase change foam.
- Double needle bar mono-filament fabric

Polyethylene closed cell foam. This has been the most popular choice for military rucksacks, but the compression and recoverability are critical and need to be highly specified. An illustration is given below:

- Typical UK figures tested to BS 4443
- Method2 Density 33±5 Kg/cu. m.
- Method 3A Tensile strength 275-450kPa
- Elongation 90% min.
- Method5A Compression Stress
- 25% 40±10 kPa
- 50% 105±20kPa
- Method 6B Compression set RT25%(24Hrec) 5-10%

Open cell foams. Open cell foams have been used extensively in the commercial world, but they suffer from a lack of durability, robustness and they absorb water, which adds weight and creates discomfort in the rain, and CW agents and are therefore unsuitable for military use. They are more comfortable initially.

Foam combinations. Foam combinations could offer a possible compromise, but the durability, water and CW agent absorption makes the choice unsuitable for the military.

Polyurethane (PU) foams. There has been a new development in PU foams called Confor foam which conforms to extreme shapes, but when the pressure is removed converts back to its original shape. This material was developed to protect drivers in Formula 1 cars. Its open cell nature could make it unsuitable for use in military rucksacks.

Phase change foam . Phase change foam absorbs body heat until all the latent heat is fully exhausted. This could prevent overheating at the interface by maintaining a constant temperature. Unfortunately, all the current samples lack durability and are totally unsuitable for use.

Double needle bar mono-filament fabric. This is the most exciting development that has occurred in novel interface materials. Although they are currently heavier than polyethylene foams, they are more durable, have better recoverability, allow the heat and sweat to escape from the body(Loughborough University evaluation) and are highly specified and controlled by the car industry. Special Forces have nominated the new “air-mesh rucksack” as their choice for the future. UK commercial companies, CQC Ltd., have begun to take advantage of this technology.

Comparison of foam/spacer fabric weights

The table below gives an appreciation of the weights of the different interfaces and aids the designer in making his or her choice.

Description	**Weight (g/sq.m)**	**Quality no**.
90patt. foam	476	
Grooved airmesh	823/760	N1702
White airmesh	605/650	N2508
Muller airmesh	686	
Black mesh face airmesh	804/750	N1685
Mesh	485	UK/SC/5188
PU Confor	1150	CF-47050

Frame choice

The most important choices when considering the frame is whether it should be external or internal, plastic or metal and any form of sizing adjustment.
The internal frame is currently favoured by most UK manufacturers and it has normally been made from metal, but more recently plastic has begun to appear. The internal frame allows the rucksack to fit nearer the center of gravity of the body. Multi-prong frames are favoured to try to improve the load distribution. External frames allow heat and sweat to escape. New integrated frames with size adjustment are beginning to appear in the UK market place.

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Biomechanical Assessment of Lateral Stiffness Elements in the Suspension System of a Rucksack

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Summary

The purpose of this study was to examine the change in load distribution characteristics associated with adding lateral stiffness elements (rods) to a rucksack. A manikin was instrumented to allow determination of the load applied to the shoulders and upper torso independent of the load applied to the hips and lower trunk. Position and mass of the payload (25 kg) was fixed at the centre of the volume of the rucksack and held constant during all testing. Results showed that this active stiffness element shifted 10% of the vertical load from the upper torso to the pelvic region with no adverse affect on other factors known to limit load carriage capacity. Lumbar shear load remained unchanged between the rod and no-rod conditions for all combinations of shoulder strap and waist belt tension. The lateral rods also provided a greater extensor moment about the medio-lateral axis at the L3-L4 level.

Introduction

A primary factor in the success of the human body carrying heavy loads is the ability to transfer the weight of the load onto the body without inducing large ancillary forces. These secondary forces result from the need to balance or stabilize the load and do not directly contribute to the vertical lift required. An optimized Load Carriage System (LCS) should minimize secondary loading on the musculature, specifically on the smaller muscle groups of the upper body. In addition to the muscular effort required to carry a load, Stevenson et al. (1997) found that a horizontal reaction force acting in the lumbar area is a major factor limiting the load carrying capacity of soldiers.

There are many advantages associated with the transfer of rucksack load from the upper torso and shoulders to the hips and lower body during load carriage. When the rucksack load is carried primarily on the pelvis, less subjective discomfort has been found to occur as compared to shoulder load carriage (Holewijn and Lotens, 1992). Sagiv et al. (1994) reported greatly reduced fatigue and discomfort compared to Epstein et al. (1988) and Patton et al. (1991) for 4 hours of treadmill walking with a rucksack under similar speed and load conditions. These differences have been attributed to a well designed waist belt and the resulting load distribution with a greater portion of the weight supported by the larger muscle groups of the hips and legs (Knapik et al., 1996). Load transfer to the pelvis is also an effective means to reduce trapezius muscle activity and high levels of contact pressure occurring at the shoulder straps (Holewijn, 1990). The use of a frame and hip-belt has been shown to decrease the incidence of Rucksack Palsy, a nerve traction injury (Bessen et al, 1987).

Objective of Study

The purpose of this study was to examine the change in load distribution characteristics associated with adding lateral rods to a rucksack. It was hypothesized that lateral rods would; provide a force bridge that transfers part of the vertical load of the pack from the upper back and shoulders to the hip belt (supported by the iliac crest) thereby reducing the vertical load on the torso, and possibly reduce the horizontal reaction force that produces a shear load on the spine.

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Methodology

The Load Distribution Manikin (shown in Figure 1) consists of a geometrically correct 50th percentile male split in the transverse plane at the level of the navel and instrumented with a six degree of freedom load cell. This apparatus allowed determination of rucksack load applied to the shoulders and upper torso independent of the load applied to the hips and lower trunk. In each of nine static configurations vertical and anterior-posterior shear force, and moment about the medio-lateral axis were obtained at the L3-4 vertebral level for both rod and no-rod conditions. Testing conditions were as summarized in Table 1. The position and mass of the payload (25 kg) was fixed at the centre of the volume of the rucksack and held constant during all testing. Shoulder strap and waist belt positions on the manikin were marked and also held constant throughout the testing. All testing was performed with ten degrees forward lean of the manikin.

Figure 1. The Load Distribution Manikin is split in the transverse plane at the level of L3-4 vertebra and instrumented with a six degree-of-freedom load cell.

Table 1. Experimental Configurations used for the rod and no-rod testing conditions.

Configuration	Shoulder Strap		Waist Belt		Sternum Strap	Load Lifter	Rod &Hip Stabilizer Straps
1	**L**	60 N	**L**	70 N	60 N	60 N	100 N
2	**L**	60 N	**M**	90 N	60 N	60 N	100 N
3	**L**	60 N	**H**	110 N	60 N	60 N	100 N
4	**M**	70 N	**L**	70 N	60 N	60 N	100 N
5	**M**	70 N	**M**	90 N	60 N	60 N	100 N
6	**M**	70 N	**H**	110 N	60 N	60 N	100 N
7	**H**	80 N	**L**	70 N	60 N	60 N	100 N
8	**H**	80 N	**M**	90 N	60 N	60 N	100 N
9	**H**	80 N	**H**	110 N	60 N	60 N	100 N

The no-rod condition is shown in Figure 2a). Upper and lower hip stabilizer straps on each side of the rucksack were tensioned to 100 N and the lateral rod attached passively on each side of the pack. The setup for the rod condition is shown in Figure 2b). The upper hip stabilizer strap was again tensioned to 100 N. The lower stabilizer strap was attached to the lower end of the lateral stiffness rod and tensioned, causing the lateral stiffness rods to become an active component of the pack suspension system.

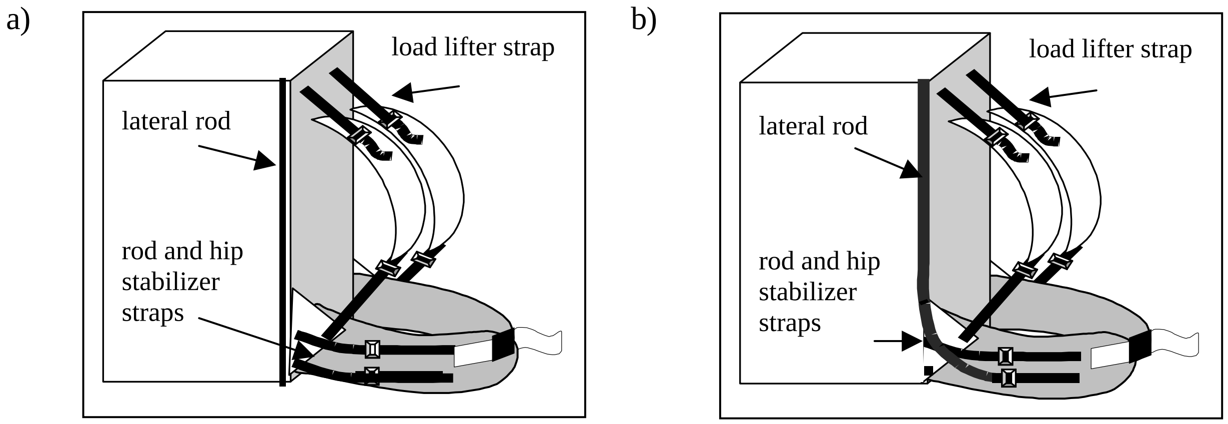

Figure 2.

a) Compression and Shear Force, and Moments acting at L3-L4 vertebra.
b) The upper portion of the lateral rod is encapsulated within a sleeve leaving the lower portion free to flex anteriorly when attached to the tensioned lower hip stabilizer strap

Results

Refer to Figure 3 for compression, shear, and moment orientations. Addition of lateral rods to the rucksack reduced the vertical load applied to the upper back and shoulders (F=77.00, p<. 05, df=1) by approximately 10% (Figure 4) without any increase in shear load at the lumbar spine (F=2.04, p>.05, df=1). An interaction effect between shoulder strap tension and 'rod vs. no-rod' conditions (F=15.00, p<.05, df=2) revealed a direct relationship between extensor moment and shoulder strap tension for the no-rod condition and an inverse relationship between extensor moment and shoulder strap tension for the rod condition (Figure 5). The main effect for the rod vs. no-rod condition (F=254.53, p<.05, df=1) revealed a greater extensor moment with the addition of the lateral rods.

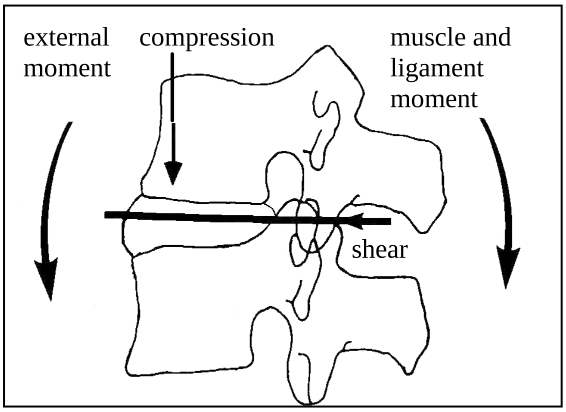

Figure 3. Compression, shear and moments acting in the L3-L4 vertebra.

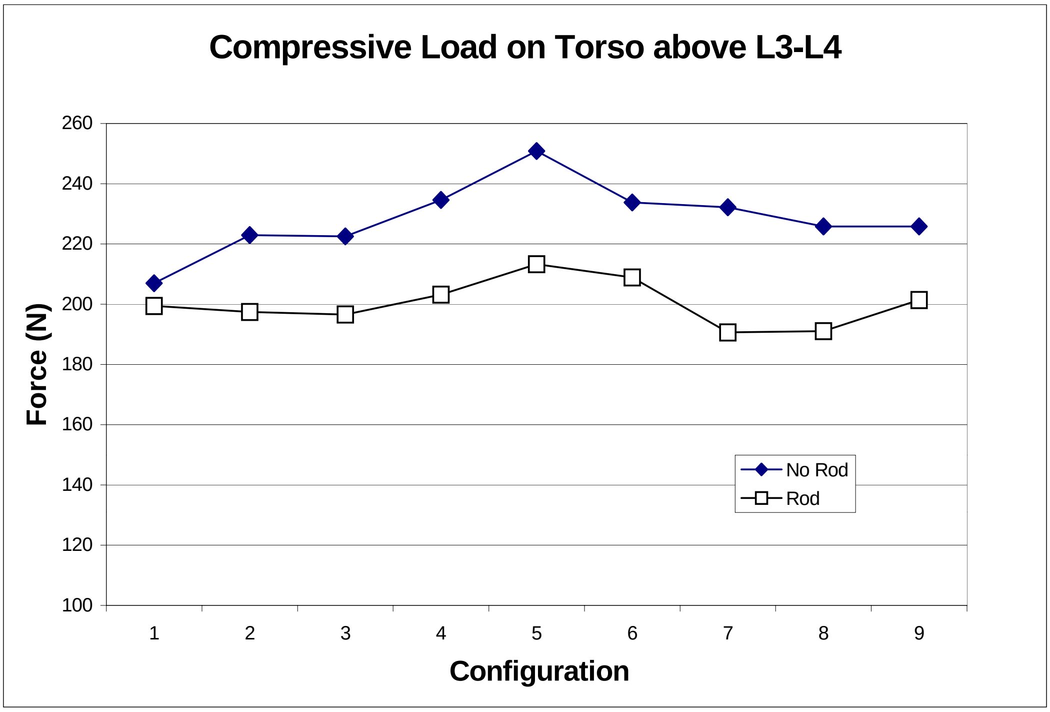

Figure 4. Vertical load force on the shoulders and upper torso for the rod and no-rod conditions.

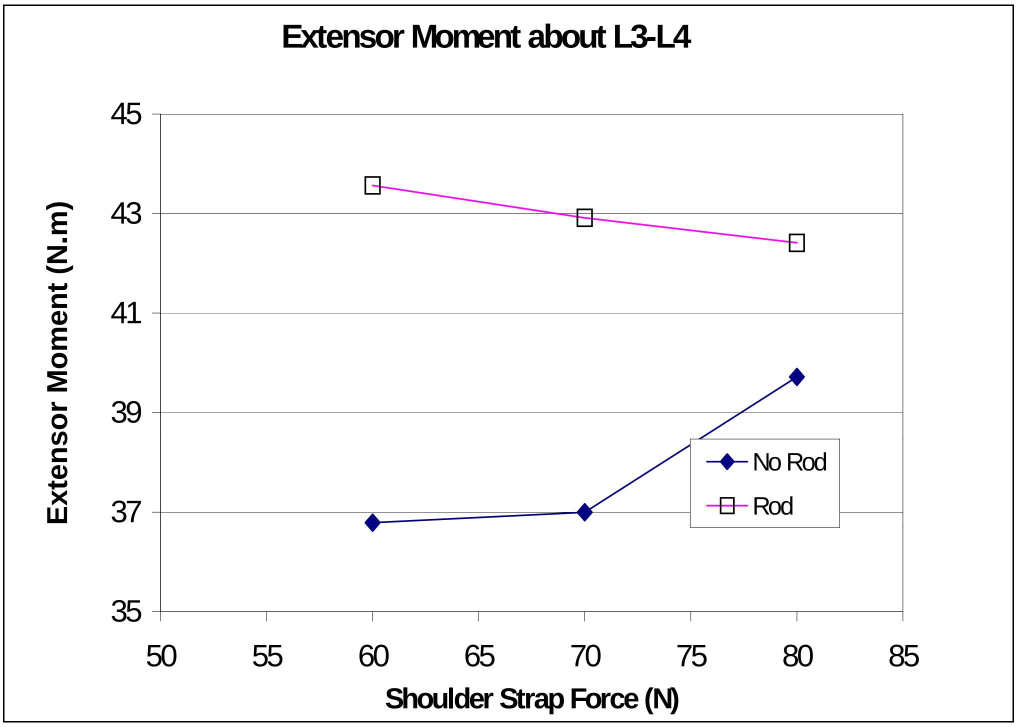

Figure 5. Anterior-posterior extensor moment for rod and no rod conditions.

Discussion

The addition of lateral rods provided a force bridge to transfer part of the vertical load of the pack from the upper back and shoulders to the hip belt (supported by the iliac crest) thereby reducing vertical load on the shoulders and upper torso during load carriage.

Lumbar shear load remained unchanged between the rod and no-rod conditions for all combinations of shoulder strap and waist belt tension. No interaction was found between the use of the rods and lumbar shear, therefore, it is likely that stiffening the rods will provide a similar benefit to a wide range of users.

The lateral rods provided a greater extensor moment about the medio-lateral axis at the L3-L4 level. Since erector spinae muscle activity has been found to increase with heavy rucksack loads in the order of 30-40 kg (Bobet and Norman, 1984), the extensor moment created by the lateral rods may provide potential to reduce low back muscular fatigue and spinal compression as load mass increases.

Continued research should be conducted on active element suspension systems to achieve a better understanding of their full potential for load carriage systems. It is possible that a much greater load distribution shift from the shoulders to the hips may be achieved through the determination of optimal stiffness characteristics for a given set of load parameters.

This study has demonstrated that an active stiffness element which bridged the shoulder and hip regions can shift 10% of the vertical load from the upper torso to the pelvic region with no adverse affect on other factors known to limit load carriage capacity. Further, the effects of the rod suspension system were limited to static characterization in this study. It is important to determine the dynamic characteristics of the rod suspension system: there may be potential to use the elastic nature of the rod suspension to conserve energy of the system, by absorbing energy in one phase of the load carriage cycle and returning stored energy in a subsequent phase.

The positive effect of rods on rucksack load distribution highlights the importance of investigating active suspension strategies to achieve improved load carriage systems. Research into a range of stiffness elements is needed to determine the optimal design, placement and characteristics to maximize the benefit of this advance. Designs could include different rod materials and cross sections, torsion or gas springs and a range of element pretensions.

Acknowledgement

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Biomechanical Assessment of Rucksack Shoulder Strap Attachment Location: Effect on Load Distribution to the Torso

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Summary

The objective of this study was to conduct biomechanical testing of pack component options to determine the optimal location for the lower attachment of the shoulder strap for the Clothe the Soldier (CTS) Integrated Patrol Pack and Rucksack. A model of a 50th percentile male torso has been split transversely at T12/L1 and instrumented with two six degree of freedom load cells. The shoulder area of the manikin was instrumented with Fscan™ sensors to record the contact pressure distribution in the axilla (armpit) and anterior of the shoulder under the shoulder strap. A 25 kg fixed payload was used for all test configurations. Waist belt, load lifter and shoulder strap tensions were constant during testing. Output variables were reaction forces at T12/L1, waist belt lifting force, average, and peak contact pressures about the shoulder. These were examined as a function of the attachment point location and as a function of the angle the shoulder strap made with respect to the body long axis. Strap angles above 30 degrees resulted in peak axilla contact pressures ranging from 35 to 64 kPa. At strap angles less than 24 degrees, anterior shoulder peak pressures of >32 kPa were recorded. These two effects determined the upper and lower bounds of an optimal range of 24 to 30 degrees with respect to the vertical axis of the body. These results cannot be extrapolated to other attachment locations that were not tested and pertain only to the type of strap tested.

Introduction

This work was undertaken in support of the major Crown Project L2646 “Clothe the Soldier” under which a number of improved personal clothing and equipment items are being acquired or developed in the near term for Canadian Forces soldiers. The objective of this study was to conduct objective biomechanical testing of a shoulder strap to determine the optimal location for the lower attachment point for the CTS Integrated Patrol Pack and Rucksack.

Scope

This study was to determine the magnitude of the horizontal lumbar force (lumbar shear) and the load share borne by the shoulders and hips for a minimum of four vertical and three horizontal locations. A total of six vertical and seven horizontal locations were tested and the results for all locations have been included in this report. Outcome measures included lumbar shear and load distribution between the upper and lower torso, and peak and average pressures experienced about the shoulder. These variables are plotted as a function of shoulder strap angle. Finally, a range of acceptable strap angles is recommended based on these results.

Method for Determining Load Distribution

Load Distribution Manikin. A model of a 50th percentile male torso has been split transversely at T12/L1 and instrumented with a six degree of freedom load cell at this location. A second six degree of freedom load cell (force plate) below the hips permits calculation of the load sharing between the upper and lower parts of the body. Additionally, the shoulder area of the manikin is covered with Bocklite™ and

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instrumented with Fscan™ sensors to record the contact pressure distribution in the axilla (armpit) and anterior of the shoulder. The experimental setup is shown in Figures 1 and 2.

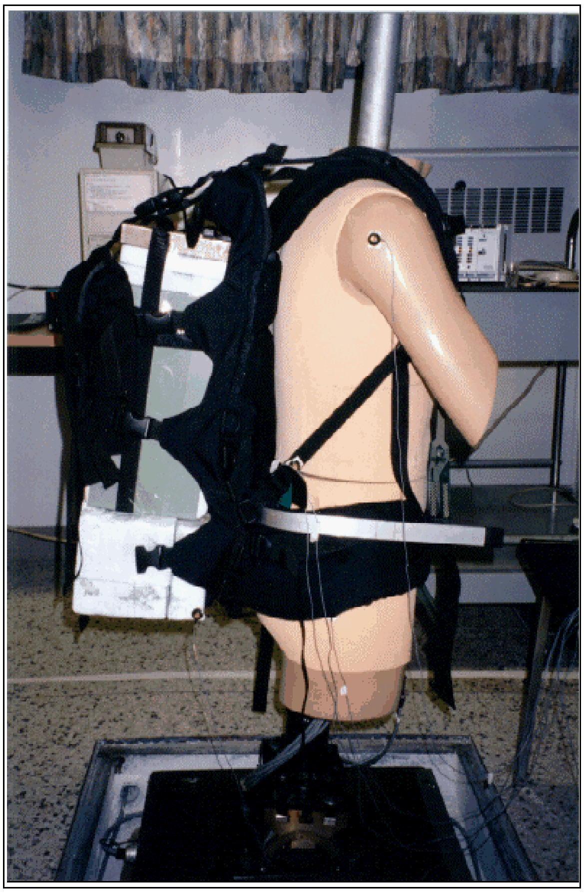

Figure 1. Experimental Setup (41 degree shoulder strap angle).

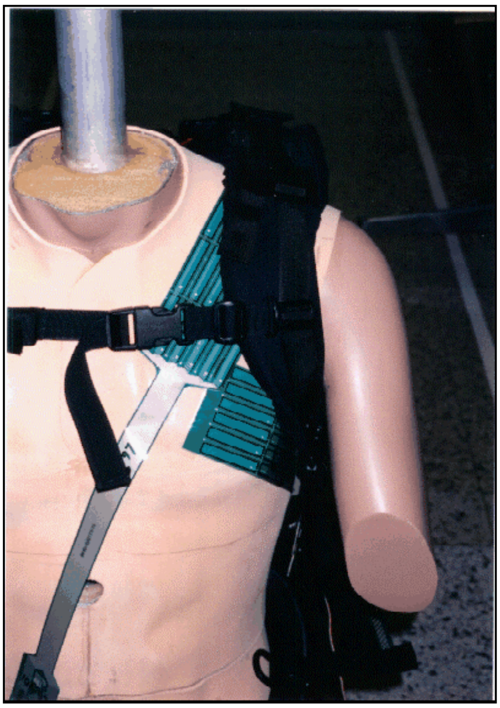

Figure 2. Load Distribution Manikin, Shoulder Detail with F-Scan™ pressure sensors

Test Protocol. Physical layout of the test apparatus and the identifiers for the attachment locations are shown schematically in Figure 3. A test pack was provided by Ostrom Outdoors that was similar to the CTS Rucksack M1 (Modular) prototype. This rucksack was equipped with a series of D-rings sewn along the vertical edge of the framesheet which allowed the shoulder strap to be moved through six vertical locations at approximately 5 cm intervals. The lowest of these corresponded to the bottom corner of the framesheet. This resulted in a vertical range of approximately 25 cm. An aluminum bar (25 x 3 mm, T6062) was placed horizontally on the pack side of the frame sheet with its lower edge aligned with the top of the waist belt. This bar was bolted directly to the two vertical aluminum stays. The outer ends of the bar were brought forward to follow the curvature of the waist belt around the hips. This bar projected forward horizontally, just above the height of the waist belt and corresponded to the third vertical position (V3). It was marked at 2.5 cm intervals and allowed a horizontal variation in the attachment point of approximately 18 cm. Horizontal location was referenced to the framesheet such that H0 was at the frame sheet and H7 was at the approximate midline of the body.

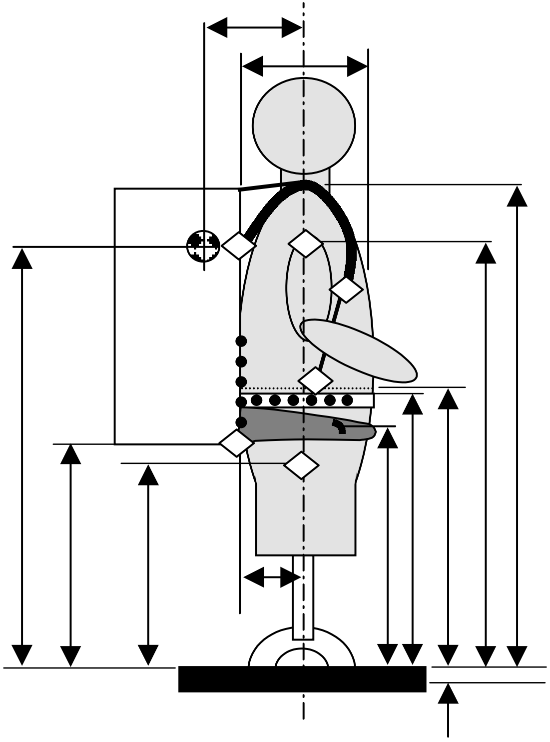

Figure 3. Schematic of Load Distribution Test Apparatus (Shoulder Strap attachment points indicated by black circles – 12 positions of varied vertical heights and horizontal positions. Optotrak position markers indicated by white diamonds).

The position and mass of the payload (25 kg) was placed at the height of the shoulder blades, as close as possible to the body for all testing. Strap tensions were set to 51 N (+/- 2) at the shoulders and 45 N (+/- 2) at the waist and recorded for all configurations. An Optotrak 3-D motion tracking system, accuracy +/- 0.1 mm, was used to measure torso lean, strap angle and pack angle. To determine these variables, position markers were placed in the locations shown as white diamonds in Figure 3.

For each test configuration, data was recorded capturing forces and moments (Fx, Fy, Fz, Mx, My, Mz) at both load cell locations, shoulder strap tension, waist belt tension and the X, Y, Z position of the 6 location markers. With the pack in place, the load distribution (LD) manikin was inclined forward using a rotational vice on the force plate until the moment about the medial/lateral axis was zero. This was achieved at 4.6 degrees forward lean. Forward lean angle remained constant for all testing as the position of the payload remained fixed for all configurations. Calibration of the load cells was done by capturing baseline data for the LD manikin with no pack at this forward lean. This baseline was then subtracted from all data. Data from the force plate was transformed using the direction cosine of the forward lean angle to rotate the force plate data into alignment with the load cell at T12/L1. Forces and moments are then reported with reference to the axis of the human spine.

The position of the centre of gravity of the pack and the manikin was determined using a force balance analysis and the load cell data for the conditions listed in Table 1.

Table 1. Calculation of Centre of Gravity

Backpack	Lean Angle
on	0
on	4.6 *
off	0
off	4.6 *

*Lean angle required for 0 anterior / posterior moment.

Results

Strap angle refers to the angle between the vertical body axis and the lower portion of the shoulder strap. The relationship between the strap angle and anatomical landmarks is shown in Figure 4.

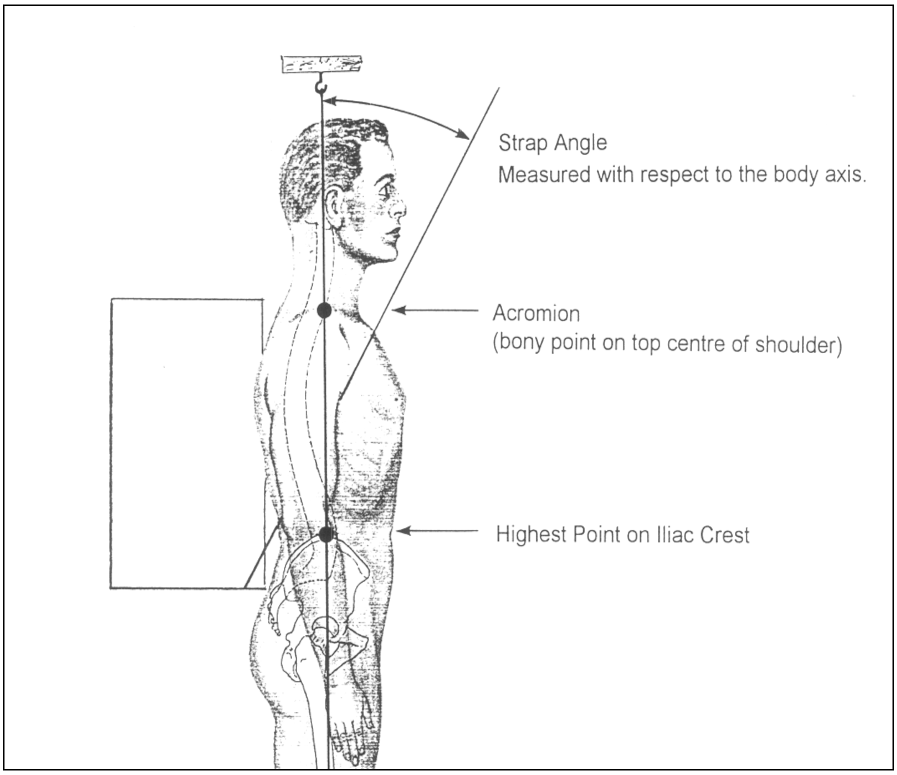

Figure 4. Relationship of Strap Angle to Anatomical Landmarks

Table 2 contains a summary of force and pressure results from the study. It includes calculated lumbar shear and compression forces over all attachment locations, the vertical lift contribution of the waist belt as well as calculated values of peak pressure, average pressure, and force experienced by the body for all the strap configurations tested. A selection of results is shown graphically in Figures 5 through 7.

Table 2. Forces and Pressure Results Summary

					Peak Pressure (kPa)		Average Pressure (kPa)		Average Body Force (N)*		
Location (horizon-tal & vertical)	Strap Angle (deg)	Lumbar Shear (N)	Compres-sive Force (N)	Waist Belt Lift (N)	Peak Anterior Shoulder	Peak Armpit	Avg. Anterior Shoulder	Avg. Armpit	Anterior Shoulder	Armpit	Total
H0V1	35.84	86.1	216.8	662.3	28.8	32	18.2	21.6	910	591.8	1501.8
H0V2	38.19	110.4	181.9	697.3	26.2	38.9	15.7	21.8	632.8	606	1238.8
H0V3	40.53	109.2	209.0	675.5	26.2	38.9	15.8	22.7	611.5	585.7	1197.2
H0V4	50.22	89.8	178.6	702.3	23.6	43.5	15.6	26	730.1	754	1484.1
H0V5	56.65	85.7	162.3	721.9	23.6	48	14.9	26.8	721.2	691.4	1412.6
H0V6	63.93	73.5	185.1	699.5	23.6	52.6	15.1	26.4	730.8	554.4	1285.2
H0V3	42.21	109.2	209.0	675.5	26.2	38.9	15.8	22.7	910	591.8	1501.8
H1V3	36.59	94.7	211.1	673.5	26.2	34.3	16.2	25.8	732.2	665.6	1397.8
H2V3	32.31	99.5	232.8	651.4	28.8	25.2	18.5	19.3	865.8	405.3	1271.1
H3V3	27.46	95.7	203.0	680.4	31.4	25.2	17.4	17.8	842.1	315.1	1157.2
H4V3	21.59	88.4	219.7	665.4	34	25.2	17.8	19.2	890	247.7	1137.7
H5V3	15.82	88.4	219.7	668.3	36.7	22.9	18.5	17.8	895.4	144.1	1039.5
H6V3	13.03	80.3	206.8	677.9	39.3	27.4	19.9	18.8	899.5	152.3	1051.8
H7V3	11.12	73.7	214.6	669.5	34	27.4	19.3	20	872.4	129	1001.4

* Body force is calculated from the F-scan data by integrating the pressure over the recorded contact area. It reflects the total load felt by the body

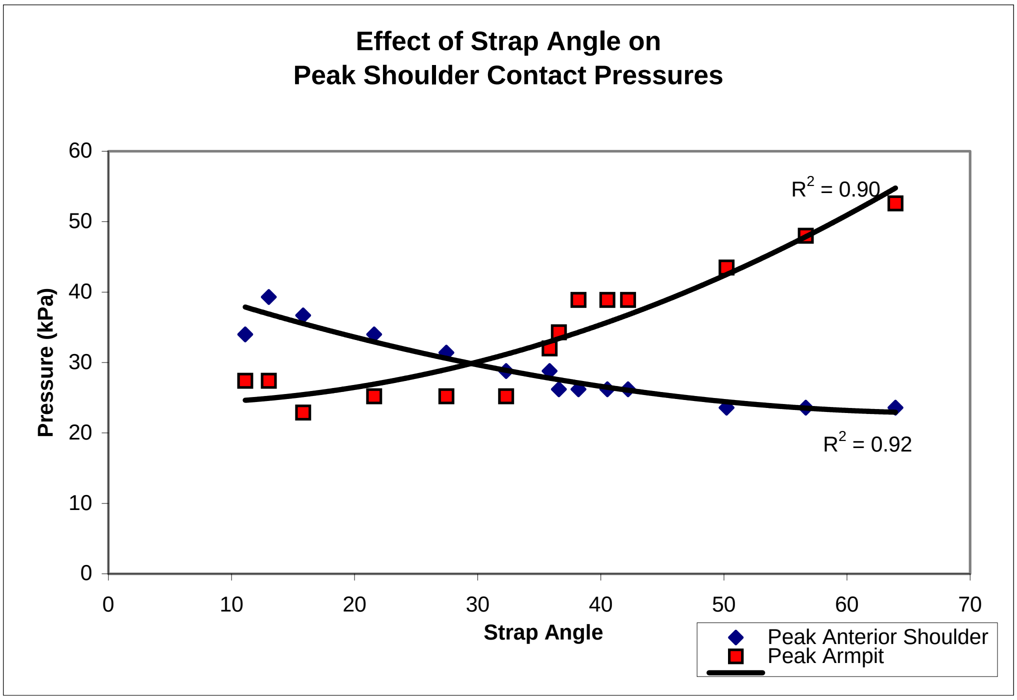

Figure 5. The effect of shoulder strap angle on peak contact pressures in the axilla and on the anterior shoulder.

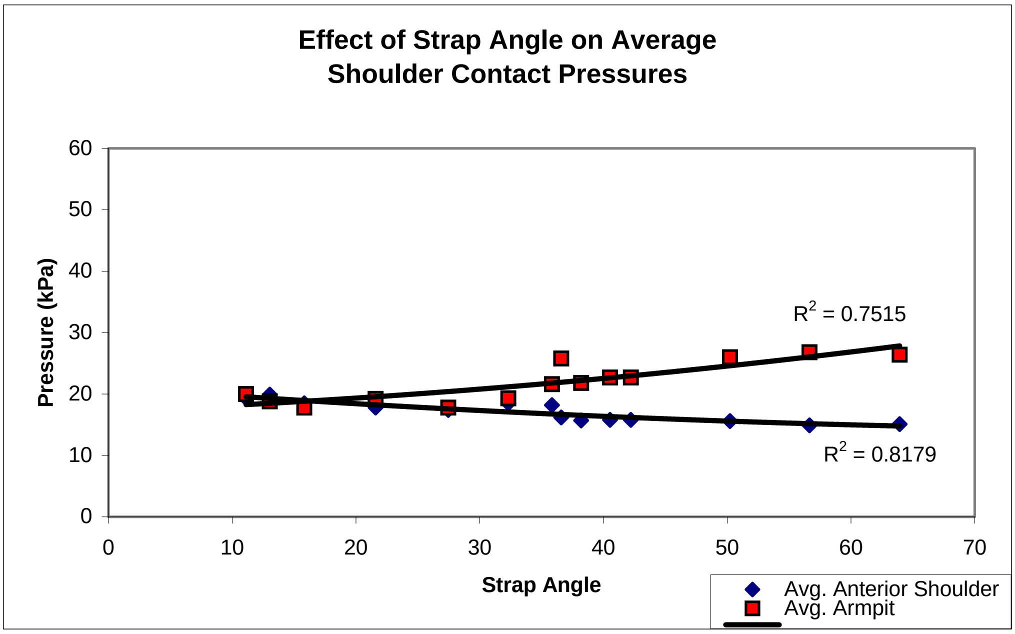

Figure 6. Effect of Shoulder Strap Angle Contact Pressures in the Axilla and Anterior Shoulder. Values greater than 20 kPa are correlated to long term user discomfort.

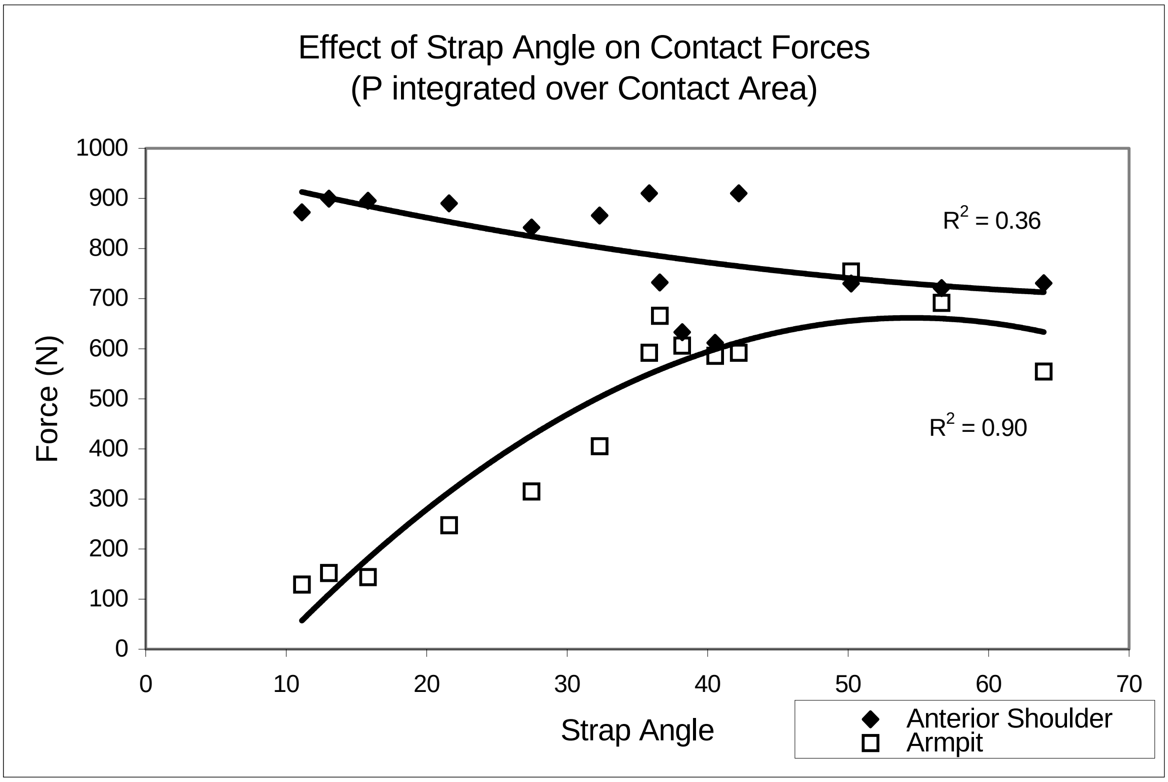

Figure 7. Effect of Shoulder Strap Angle on the force experienced by the body. These values are calculated by integrating the recorded pressure over the contact area.

Discussion

Comparison to Threshold Limit Values. As seen in Figure 5, attachment points with strap angles higher than 30 degrees resulted in increases to peak skin contact pressures in the axilla. Anatomically, this corresponds to having an attachment point above the height of the iliac crest. This result is consistent with the direction and relative magnitude of the body's shoulder force predicted in the biomechanical model developed by Stevenson et. al. (1995). The peak contact pressures values measured in the axilla at strap angles greater than 30 degrees ranged from 35 to 64 kPa. These values are expected to result in significant discomfort for users. This was used to select an upper bound of 30 degrees to the recommended strap angle.

A study by Holloway et al. (1976) suggests that a safe physiological contact pressure limit for continuous pressure over 8 hours is 14 kPa, while the average contact pressure threshold limit for the perception of pain was determined to be approximately 20 kPa in work by Stevenson et al. (1997). Average contact pressure on the axilla (Figure 6) began to exceed 20 kPa at strap angles greater than 30 degrees. This was consistent with the results for the peak pressure distribution.

As shown in Table 2, the magnitude of lumbar shear force decreased as strap angle decreased but this was tied to an increase in the load experienced by the anterior shoulder. Figure 5 shows that at strap angles less than 24 degrees, peak anterior shoulder pressures approached 32 kPa.

A previous study (Stevenson et al., 1995) also determined a maximum allowable value of 135 N for transverse loads on the spine based on achieving optimal human load carriage performance. Although no attachment location resulted in a lumbar shear force greater than 135 N (see Table 2), there was a twofold change in the magnitude of the lumbar shear over the range of strap angles tested.

Figure 7 illustrates how the change in shoulder strap angle affected the total load experienced by the shoulder region. Although the top front of the shoulder unloaded, the load on the axilla increased at a greater rate, causing an increase in the total load experienced by the body at higher strap angles.

These factors were used to determine a recommended lower bound on the optimal strap angle range of 24 degrees. Strap angles of 24-30 degrees can be achieved in two configurations: with the attachment point at the lowest point possible on the pack; and when the attachment point was moved forward towards the body midline. In the test rucksack provided, the strap angle was 35 degrees at the lowest point possible on the pack and would have to move an additional 5 cm lower to reach the optimal range.

Conclusions and Reservations

The study concluded that:

- The optimal configurations for load distribution to the body resulted when the lower part of the shoulder strap achieved an angle of between 24-30 degrees with respect to the vertical axis of the body; and

- Strap angles in this range can be achieved by locating the attachment point at locations V3H2 and V3H3, just posterior to the body midline at the height of the iliac crest. A strap angle of 35 degrees was achieved at the lowest point on the pack frame sheet as tested. If this location were an additional 5 cm lower, the resulting strap angle would be within the optimal range.

Note that only single measures were recorded at each configuration. This limits the strength of conclusions based on these data. Additionally, these results cannot be directly applied to other possible attachment locations that were not tested.

Acknowledgement

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Biomechanical Assessment of the Canadian Integrated Load Carriage System using Objective Assessment Measures

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Summary

The purpose of this study was to provide an overview of contributions by biomechanical testing to the design of the final Canadian Clothe the Soldier (CTS) load carriage (LC) system. The Load Carriage Simulator and Compliance tester were used during design of the CTS system for evaluation of: three fragmentation vests, seven Tactical Vests and three iterations of the rucksack. Test data were compared to a data pool of previously tested systems. Results indicated that the objective measures helped the design team by: 1) understanding the consequences of various design changes; 2) predicting soldiers’ responses to design changes in pressure, force and relative motion; 3) comparing this system objectively to other systems; and 4) providing information quickly so that ideas could be incorporated into the next design iteration. It was concluded that objective assessments added valuable information not easily interpreted from human trials. However, objective assessments cannot replace human trials for feedback on functionality and features.

Introduction

The Canadian Defence and Civil Institute of Environmental Medicine (DCIEM) undertook a research and development program on advanced personal load carriage systems as a part of their soldier modernization efforts. Their goal was to improve soldier’s personal equipment by better integration of load carriage components and improved protection within the load carriage system for soldier safety in future conflict or peacekeeping operations. The Canadian soldier modernization program involved two components: upgrading the current soldier system under Crown acquisition project L2646 Clothe The Soldier (CTS) and developing future soldier systems under Crown project D6378 Integrative Protective Clothing and Equipment (IPCE).

The task assigned to Queen’s University was to develop a cost effective, quantitative and reliable method by which various load carriage equipment designs could be evaluated and recommendations integrated into further design iterations. In this regard, Queen’s joined part of a comprehensive team, led by DCIEM, that included designer/manufacturers (Pacific Saftely Products, for the load-bearing and fragmentation protective vest designs, and Ostrom Outdoors Inc., for the design of the integrated patrol pack and rucksack), human factors assessment specialists (Human Systems Inc.), and the necessary military portfolios needed to develop a new modernized CTS load carriage system. The design team was structured with DCIEM taking the lead. Prototypes and design ideas were evaluated by a series of biomechanical tests at Queen’s University, and by via focus groups and field trials with soldiers at a number of military bases (Figure 1). The designer was asked to respond to the design changes needed based on either the biomechanical analysis or soldier feedback. By this model, soldier input was central to and incorporated into the design process.

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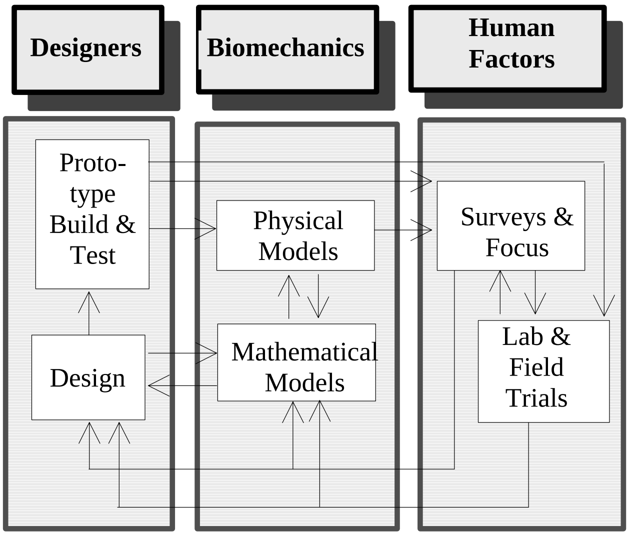

Figure 1. Model of interactions and responsibilities of DCIEM's CTS Load Carriage System Design Team.

The purpose of this paper is to provide an overview of contributions by biomechanical testing to the final Canadian CTS load carriage (LC) system design. The work plan was structured to complete the design iteration process as quickly as possible (within a year for each item), so rapid objective feedback was essential. The overall goal of the project was to conduct various biomechanical assessments of components and total LC system in order to improve design concepts through objective biomechanical assessments, comparison to a data pool of other LC systems and integration of components.

The specific purposes of the study were to use the standardized biomechanical simulations to evaluate: 1) three fragmentation vests currently in the evaluative process by the Canadian military; 2) seven webbing or load carriage vests under two conditions; with and without a fragmentation vest; and, 3) three iterations of the final CTS rucksack. In all cases, investigators gave feedback to the design team about the results of evaluations and compared the design iteration to the database of other LC systems. In addition, potential soldier discomfort concerns and compatibility problems were identified as well as possible design solutions or enhancements.

Methods

The testing program for each sub-study was selected to provide the most appropriate feedback relating to conditions of use. Two assessment tools will be described briefly as well as their test protocols.

Load Carriage Simulator. The Load Carriage Simulator was designed to capture the impact of a LC system on the human torso based on normal gait motions. It is a standardized assessment tool that allows researchers to evaluate the impact of different designs on human performance. The LC Simulator outcome measures were validated against soldiers' subjective responses and this information was reported by Bryant et al.[1, 2] It is an innovative design using a computer-controlled pneumatic system that can be programmed to walk, jog or run in a sinusoidal pattern reflecting the human gait pattern[3]. A 50th percentile anthropometrically adjusted male hard-shelled mannequin was covered with a skin analogue Bocklite™ and mounted onto a six degree of freedom AMTI load cell. The load cell, attached between a pivoting base plate and the mannequin, measured forces (F_x F_y F_z and F_R) and moments (M_x M_y M_z and M_R) at the hips about the principal trunk axes. Tekscan 9811 pressure measurement sensors were place over the shoulders, upper and lower back, and waist area in order to measure average pressures, peak pressures as well as average contact forces in each area. Relative displacement of payload items in the LC system were measured using up to four Polhemus Fastrak™ magnetic sensors, which were placed on specific kit items for fighting order assessments and one in the pack for marching order assessments. The six degree of freedom movement of the described the motion of the payload and kit items relative to the mannequin during gait.

The protocol for LC Simulator testing involved: a) carefully dressing the mannequin with the test gear, b) tightening the shoulder, waist and other straps to standardized tensions based on in-line strain gauges, c) balancing the anterior/posterior moment to zero for each test condition thus simulating a balanced load, and d) collecting five repetitions of 10 seconds of data every 5 minutes at data acquisition rate of 50 Hz. The speed of LC Simulator motions was standardized at 3.5 Hz for jogging simulations and at 1.8 Hz for walking simulations. Post-processing of raw data was conducted on all outcome measures and these data were compared to a previously collected database of other packs tested under the same conditions.

Load Carriage Compliance Tester. The LC Compliance tester was designed to examine the natural stiffness of a pack suspension system and can also be used to examine the resistance of a fragmentation vest or load carriage vest to trunk flexion, lateral bending and torsion motions. The LC Compliance tester was validated against human trials and the rigidity of the system was inversely correlated ($r^2 > 0.86$) to several performance variables such as: users' comfort and ability to perform whole body and arm motions[4].

The LC Compliance tester is an articulated 50th percentile torso that is covered with Bocklite™ and bends forward and sideways at a L3/L4 level and in torsion around a L4/L5 level. Using a cable-pulley system and a preset load of 5 kg, the upper body is rotated around one axis at a time to: a) 48° of flexion, b) ±18° of lateral bending and c) ±12° of torsion.

The testing protocol involved: a) taking a baseline without a LC system in place, b) mounting an empty LC system on the Compliance tester with standardized strap tensions, c) collecting three trials of data for each condition around each axes of motion, d) subtracting the baseline resistance of the test equipment from each trial, filtering and averaging the trials, e) assigning the best fit regression equation to the data, and f) reporting the bending stiffness in Nm/deg for each axes of motion.

Part 1: Assessment of Fragmentation Vests

Introduction. The purpose of this study was to examine three designs for the fragmentation (Frag) vest both objectively and subjectively. The Frag vests under review were: the current Canadian vest (Gen-2) and two new prototypes, Gen-3A and Gen-3B. The design concept was built from the human body outward. The main differences in features between vests were: the Gen-2 had overlap junctions of front and back panels at the shoulders and a removable neck guard, the Gen-3A had side junctions and a lower profile removable collar and the Gen-3B had an asymmetric left side shoulder and side junction closure. To create a realistic and standardized testing condition, a mesh style of Tactical Vest (with a payload of 98 N) was worn over each Frag vest. This study is available from DCIEM in more detail.[5]

Methodology. To examine the dynamic responses of the three Frag vests and their impact on the user, the LC Simulator was used. The 50th percentile mannequin was programmed for 6 km/hr (3Hz) jogging. Data were taken from the relative displacement sensors, the pressure sensors, and the hip forces and moments. To examine body motion restrictions due to design, the LC Compliance tester was used to collect stiffness characteristics of the three Frag vests. To gather user discomfort information and additional factors related to mobility, test subjects completed components of the battlefield circuit and submitted individual Likkert Scale responses and focus group feedback.

Results and Discussion. Table 1 provides a summary of the rank order results for three Frag vests. There were negligible differences between Frag vests for relative kit motion and hip moments and shear forces, but the pressure system indicated high pressure points. The Gen-2 vest had local pressures of 70 kPa in the collar area because of seams and edges and the Gen-3B had over 89 kPa on the left shoulder at the closure juncture. The overlapping of the ballistic layers caused a discontinuity that exerted high pressures when the shoulder area was loaded by additional load carriage equipment. Since over 16 kPa can cause complete cessation of blood flow to an area[6], and 90% of soldiers reported discomfort with over 20 kPa of average pressure for a 6 km march[7], then these point pressures will cause complaints and possibly injury to the skin. For peak pressures, 35 kPa was the level where soldiers would begin identifying discomfort and only the Gen-3A vest did not exceed that recommended limit for peak pressure[5]. In the human trials, subjects reported interference between specific kit items of clothing and equipment and Frag vests and occasional reports were that ballistic layers and edges were poorly positioned for comfort. In addition, the shoulder closures on the Gen-2 and Gen-3B vests were considered to be uncomfortable.

Table 1. Summary of rank order results for three fragmentation vests.

Variables	Gen-2	Gen-3A	Gen-3B	Discussion
LC Simulator Measures				
- Displacement (mm)	2	1	3	Negligible motion for all Frag vests
- Peak Pressure (kPa)	2	1	3	Collar (GenII), shoulder closure (GenIIIB)
- Forces & Moments	1	2	2	Negligible effects for all Frag vests
LC Compliance Measures				
- Forward (Nm/deg)	1	2	2	GenIIIA & GenIIIB extend down torso
- Lateral (Nm/deg)	2	1	3	Side closures reduce stiffness
- Torsion (Nm/deg)	3	1	2	GenIIIA had larger gap at waist with fastener
Human Factors				
- Subjective Reviews	3	1	2	Shoulder closures were uncomfortable One buckles on TV created a pressure point

Conclusion. In conclusion the Gen-3A Frag vest was recommended to the CTS design team with specific improvements. This phase of the research feedback was provided to DCIEM within two weeks of receiving the equipment.

Part 2: Assessment of Tactical Vests

*Introduction***.** The purposes of this study were: 1) to evaluate the impact of wearing or not wearing a Frag vest underneath a Tactical Vest; and 2) to assess seven vest or webbing-based systems with objective measures. For this study, seven tactical assault systems were assessed: three short vests (SV1, SV2, SV3), two waist length vests (LV1, LV2), and two sets of webbing (Web1, Web2). The Gen-2 Frag vest was used for assessment of the effectiveness of the system with or without a fragmentation protective vest. As with the previous study, the objective was to provide the test results to the design team quickly, as well as uncover potential problems or compatibility issues, and make design recommendations. This study is available from DCIEM in more detail.[7]

Methodology. Only the LC Simulator was use in this study under jogging conditions comparable to 6 km/hr (3 Hz). Each tactical assault system was assessed with a payload of 7.33 kg consisting of the following kit items: one C-9 magazine, four C-7 magazines, one water canteen, two smoke grenades, two fragmentation grenades, and miscellaneous clothing. The four Fastrak™ motion sensors were placed within non-metallic casements in the C-9 magazine, the water canteen and in two C-7 magazines. The outcome measures were: a) total kit motions in x,y,z and the vectoral sum r of the motion; b) forces and moments at the hip level from the AMTI load cell; and c) peak pressure, average pressure and contact area of the Tactical Vests from the Tekscan™ pressure measurement system. In addition, each configuration was checked for compatibility both visually, in terms of geometry, conflict with the shoulder strap or waist belt and other conflicts, and in terms of battle relevant tasks such as accessibility, restriction of motion, interference and comfort.

Group data from all seven systems were submitted to a paired t-test comparison with a Bonferroni correction for multiple applications. Based on this correction, $p>0.017$ was accepted for significance.

Results and Discussion. Figure 2 is a graphic representation of the impact of wearing a fragmentation vest on all LC Simulator outcome measures. There was no statistical significance between the Frag and no Frag conditions, except for the net reaction forces and moments. Naturally, these outcome variables would be impacted by the weight of the fragmentation vest and the moment necessary to control it. The variables of total kit displacement, and peak and average pressures were not significantly affected by wearing the fragmentation vest. It would appear that both motion of the payload and skin contact pressures are unchanged by wearing a Frag vest but added weight and added heat load may affect soldier comfort or performance. This is a moot point in battle when personal safety (via evading or returning fire) is the paramount concern. However, during non-combat conditions, soldiers would have an increased physiological demand on their bodies while wearing the fragmentation vest.

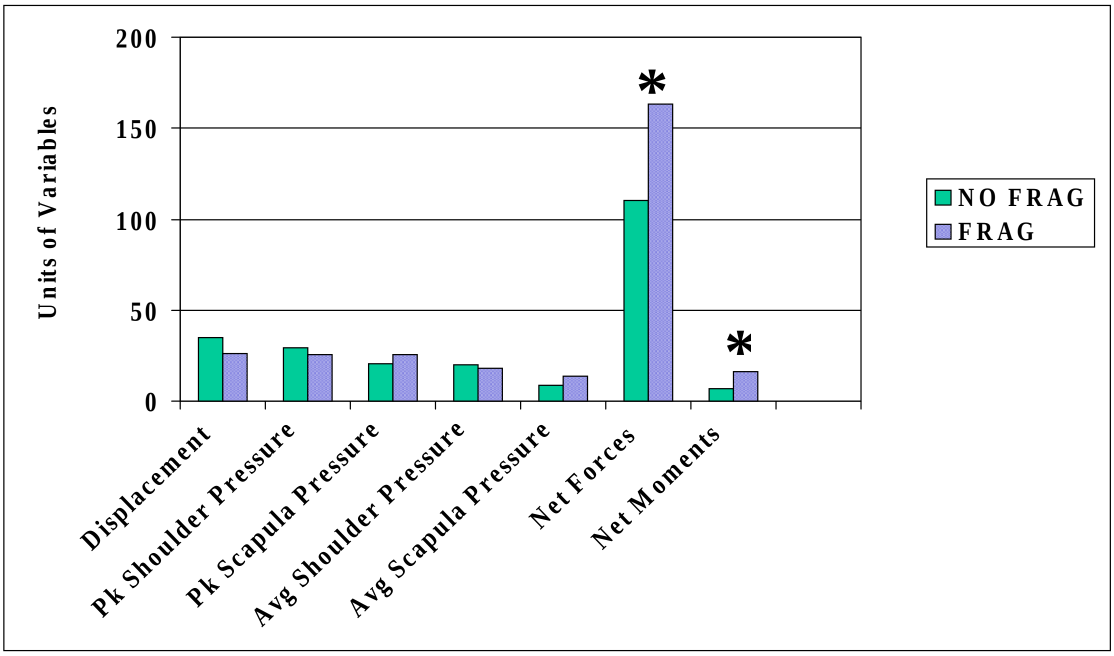

Figure 2. Effect of Wearing a Fragmentation Vest on LC Simulator Measures

The objective variables from the LC Simulator test that will be presented include net relative displacement and average pressure over the combined anterior and posterior shoulder region. Only the top two rankings will be discussed with reasons given for their ranking. The Frag/no Frag conditions were combined in the ranking except for forces and moments where there were significant differences between conditions.

Figure 3 depicts displacement of the payload relative to the mannequin for each of the seven Tactical Vests under Frag and no Frag conditions. When examining the net displacement of the kit during jogging, SV3 had a combined best score showing the least relative motion during jogging under both Frag/no Frag conditions. The second best system was LV1, but in this case the fragmentation vest served to reduce the relative motion between the kit and the mannequin. In most other cases the relative displacements of the kit items moved more on the soldier without the fragmentation vest.

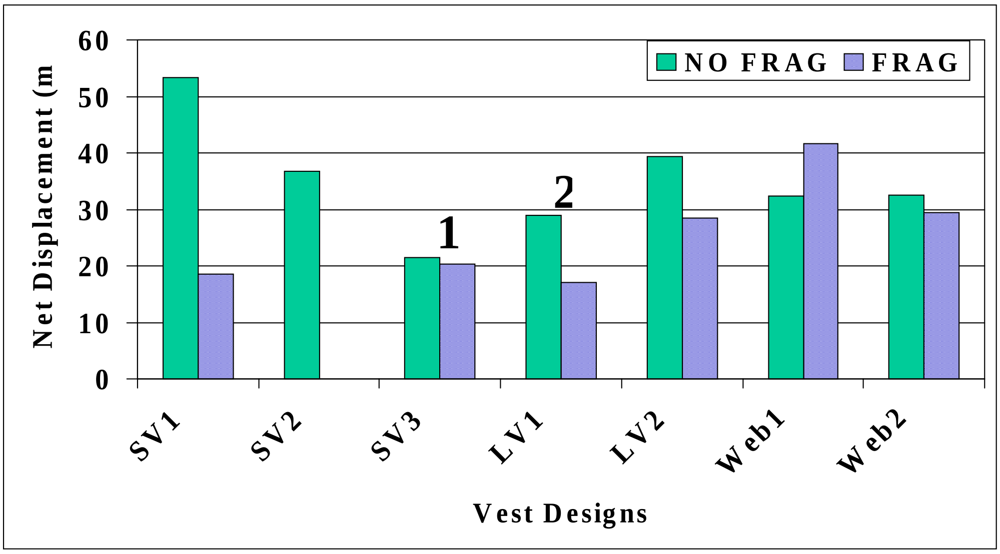

Figure 3. Effect of Tactical Vest Designs on Net Relative Kit Displacement

Figure 4 shows the average shoulder pressure when the anterior and scapular regions are combined. The top ranking systems were SV3 followed by the Web2, a webbing-based system. Maintaining a low average pressure is important since 90% of soldiers report discomfort at 20 kPa of pressure[8]. This means that only the SV3 was within recommended limits for both conditions. The importance of keeping the average shoulder pressures at a minimum in fighting and battle order is critical if one considers that the rucksack will also add to the shoulder pressure that soldiers will experience in the marching order of dress[1].

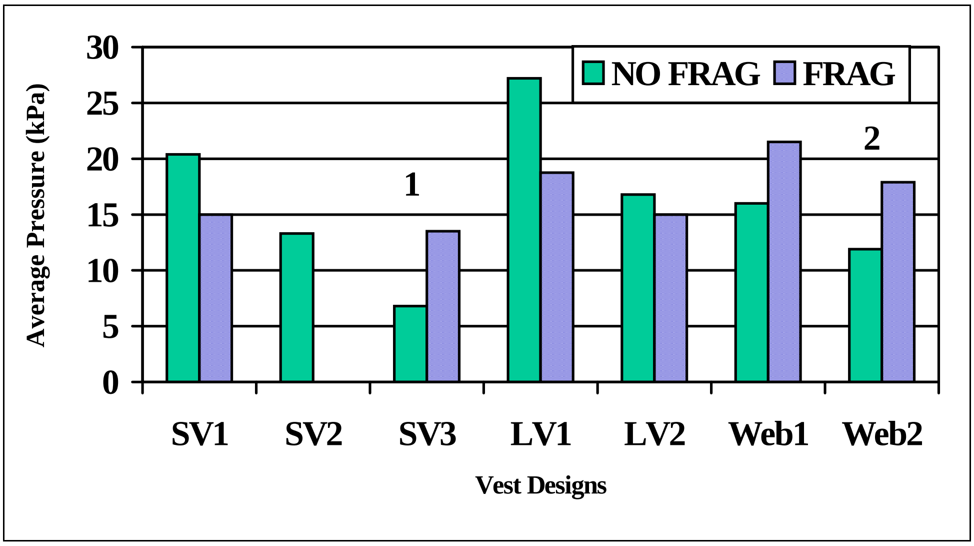

Figure 4. Effect of Tactical Vest Designs on Average Shoulder Pressure

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[1] Fighting, Battle and Marching Order refers to the "order of dress" or standardized clothing & equipment carried to sustain soldiers for 8, 24 or 72 hours respectively. Fighting Order typically involves webbing or vest alone. A patrol pack or added storage pouch is added to make up Battle Order. Marching order adds the rucksack to the former dress conditions.

In terms of compatibility, the investigators observed laxity in the attachment of various kit items, specific pressure hotspots of concern with each fighting order system, and interference between specific kit items when the fragmentation vest was worn. In terms of human trials, results confirmed that there were similar hotspots to those identified on the LC Simulator; soldiers reported LC vest systems that had excessive looseness of the kit, as well as difficulty making certain movements during some of the battle order tasks.

Conclusions. In conclusion, based on the objective data, and limited human factors data, the SV3 vest was recommended to the Canadian Forces under the following conditions: 1) that SV3 be designed with protected spaces for the shoulder straps, waist belt and back support area to receive the backpack; 2) that shoulder stitch locations and a padded shoulder design be implemented to reduce shoulder pressures; 3) that the conflict be removed between the SV3 vest and C-9 magazine and 4) that the Gen-2 fragmentation vest collar and ballistic material ridges be modified to overcome problems relating to comfort. These changes were implemented before the team continued with military focus groups and field trials in order to get feedback on final design features. After these trials, a modified SV3 was renamed and became the Tactical Vest for the final system. Only three weeks of objective testing were needed to give the DCIEM design team initial feedback on the Tactical Vest study.

Part 3: Evaluation of Rucksack Designs

Introduction. As part of the overall design process, various iterations of the rucksack were developed and tested by both human trials and standardized objective measures. Prior to commencing the study, the designer had requested that several commercial packs be assessed by the Queen's Ergonomics Research Group biomechanical testing centre. The database of backpacks was, therefore, advanced to include both civilian and military systems. In total, 17 systems were in the database prior to comparative studies with prototypes of the CTS rucksack design. In previous steps, the design team had identified protected spaces on the SV3, now called the Tactical Vest (TV), that were necessary to accept the shoulder straps, waist belt and back support area for the backpack. The purpose of this study was to assess three designs of the CTS rucksack with objective measures and to recommend solutions to design problems prior to development of the next iteration. This information is also available in greater detail in a DCIEM report.[9] There were also sub-studies to examine specific design questions such as, the optimum location for the lower shoulder strap attachment point and the effect of the addition of lateral rods into the suspension system. These studies have been reported by Reid et al.[10,11] .

Methodology. The three prototypes, models K, M and F, designed by Ostrom Outdoors Inc. of Nolalu, Ontario were sent to Queen's for appraisal. Model K was the "keep it simple" design, the Model M was the "modular system" and Model F was the final model that had features from both of the previous versions. A combat shirt and the previously tested Tactical Vest (TV) were worn under the packs during all tests.

Prior to testing, the mass properties of the system were taken that included the mass of the pack plus payload, its' centre of gravity and the physical dimensions. The systems were carefully adjusted to suit the 50th percentile male mannequin size and with standardized strap conditions of 60 N per shoulder strap, 50 N on the waist belt, 100 N per hip stabilizer strap, 60 N per load lifter strap and 60 N on the sternum strap. The standardized test protocol as implemented for both the LC Simulator and LC Compliance Tester. Visual inspections for compatibility and brief human trials were also conducted. The three models, K, M and F were compared to one another and to the pooled database. Each prototype was compared to the mean of the data pool for each correlated variable and the lower 10% of inferior packs and upper 10% or superior packs.

Results and Discussion. Only the most relevant correlated results will be compared in this paper but greater details are available within the DCIEM technical reports[12,13,14]. Figure 5a shows the stiffness of the suspension systems in Nm/deg in flexion, lateral bending and torsion as taken from the LC Compliance tester. All stiffness measures were highly correlated to mobility, load control and comfort dealing with load transfer. Although the prototype systems were not considered superior, they were not substantially handicapped by the inclusion of lateral rods in the suspension system. This means that the pack frames' resistance to gait and mobility motions were above average around all three axes. The poorest performers in pack frame stiffness about all three axes were some military systems and external frame packs.

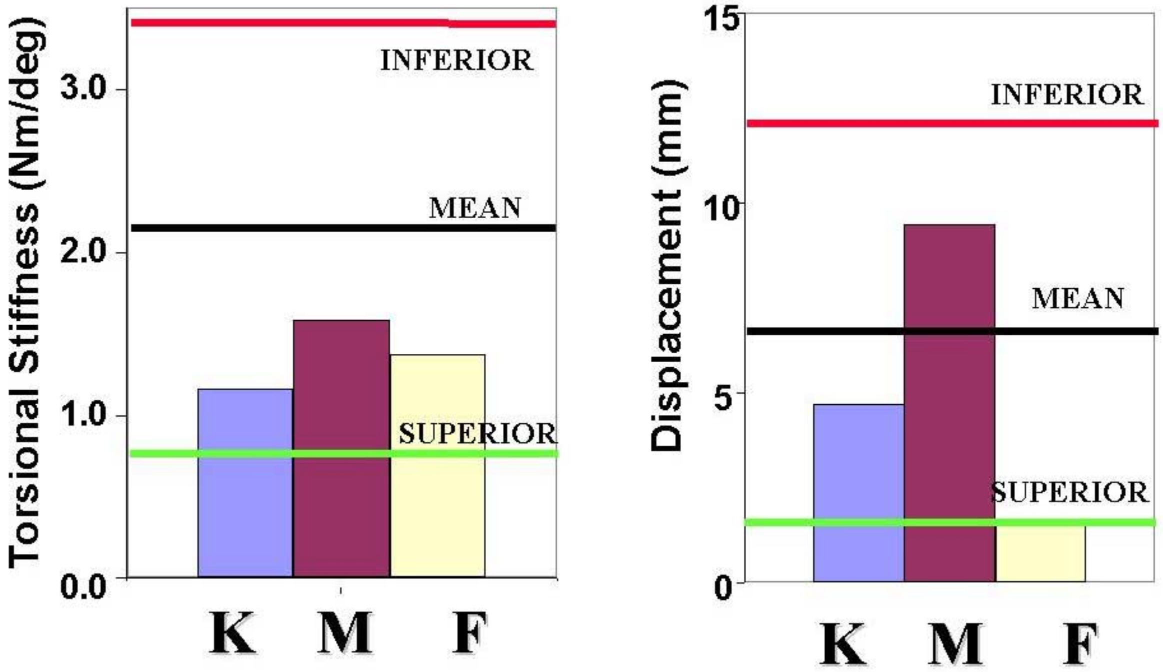

Figure 5a. Suspension Stiffness from the LC Compliance Tester.
Figure 5b. Relative Pack Displacement from LC Simulator

Figure 5b displays the resultant relative displacement in millimeters between the pack and person for the K, M and F systems. This variable had been shown to be related to hip discomfort, probably due to transfer of impact loads to the lumbar pad and hip region of the waist belt[8]. Minimal relative pack motion is characteristic of a stiff suspension system, a factor that was evident by the difference from the modular M pack to the Model F. Load control is improved with a stiff suspension system because it will move in response to the soldier's trunk motion. In this regard, Model F was superior as it fell within the top 10% of packs in the database.

Figure 6a is a selection of one average force variable (Fz) as a representative of the average force and moment data from the load cell at the hips. These outcome variables have been shown to be correlated to overall mobility, balance and overall comfort. The model F design had a very stiff suspension system that transferred higher vertical loads to the body. As model F induced higher vertical reaction loads than other packs in the database, it was ranked as inferior in transmission of vertical (Fz) forces through the spinal column but it was superior in side to side (Fy, Mx) control. It is easy to see the logic of maintaining small side to side forces and moments for good pack control. However, the interpretation that higher average Fz forces for backpacks are problematic may be incorrect, given that basic research studies have shown the tissue tolerance limits for compression of a straight spinal column to be higher than other axes and hence may be able to withstand high forces without injury[15]. The F model pack was superior in My flexion/extension moment that would keep spinal shearing forces to a minimum[14]. If the compressive Fz forces through the spinal column are not a problem, for the backpack wearer, then the cause of soldier discomfort scores in the current database needs further examination. Further human studies would be helpful to understand and explain this relationship.

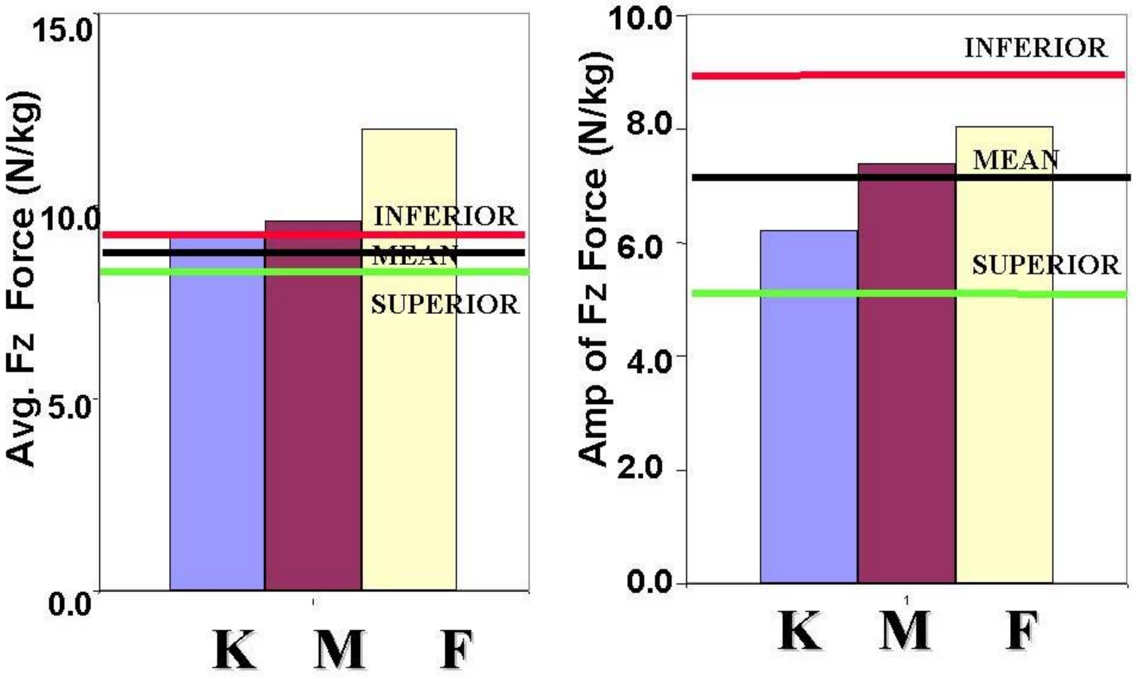

Figure 6a. Average Force (Fz) from the LC Simulator.
Figure 6b. Amplitude of Force (Fz) from the LC Simulator.

Figure 6b is a representation of force and moment amplitudes and of the three CTS prototypes in comparison to database systems. The amplitudes of x, y, z moments in Nm/kg and the z and r forces in N/kg were correlated to load control such as balance, mobility, and maneuverability[8]. The three prototypes were consistently below average or inferior indicating that there was a substantial dynamic component experienced by the hips. This was not reflected in the shoulder pressure average profiles nor in the relative displacement of the pack, indicating that the pack suspension system was absorbing most of the oscillating forces and moments. Kram[17] proposed that that a dynamic suspension system could be helpful to return mechanical energy to the body through use of bamboo poles. In a sub-study that was designed to examine the effects of lateral rods in the suspension system, Reid et al.[9] found reduced vertical compressive force Fz and increased extension moment My at L1 with the use of these rods. If these amplitudes can be controlled, then it is possible that a tunable dynamic suspension system could be created. Further research is needed to investigate this theory.

Figure 7a is the average anterior shoulder pressure and Figure 7b is the peak anterior shoulder pressure summarizing the pressure profiles experienced by soldiers wearing the prototype systems. From previous studies collated into the database, five shoulder pressure measures and two lumbar pressure measures were related to soldier reports of discomfort, especially in the posterior hip and neck regions, and a reduced ability to doff the pack[8]. In all contact pressure variable studies, the three systems ranked in the superior category. During the CTS design cycle, there were two sub-studies that may have helped generate this positive result. In one study the optimum location for the lower shoulder strap attachment point was selected to reduce lumbar shear and minimize peak loading of the anterior shoulder/axilla region[10]. In the second study, three types of strap shapes were investigated to reduce the contact pressure profiles[16]. In addition, the meticulous care devoted to integrating the strap configurations with the straps of the TV may also have contributed to prototypes' superior performance.

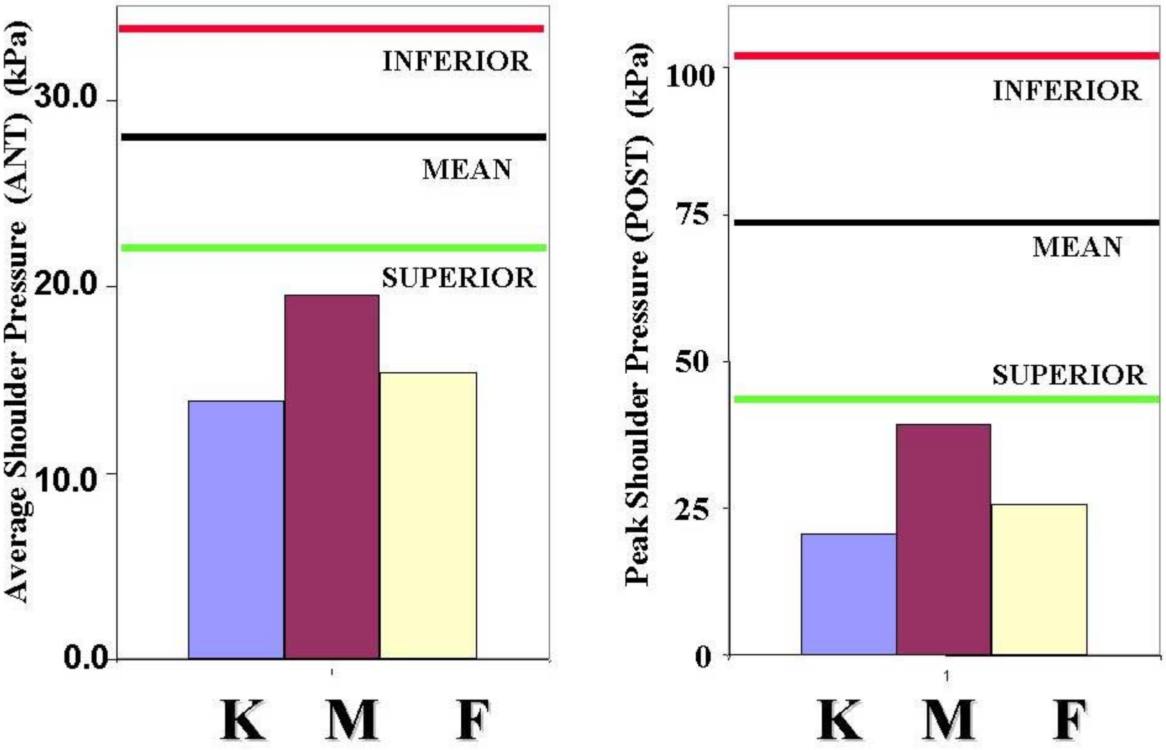

Figure 7a. Average Anterior Shoulder Pressure from LC Simulator.
Figure 7b. Peak Posterior Shoulder Pressure from LC Simulator.

Conclusions. In summary, the model F was a composite of features from the previous prototypes. It was designed to have one large storage compartment with two openings (top and front) and a number of detachable storage pouches for modularity. The CTS pack system had load-lifter straps, sternum and hip stabilizer straps. The suspension system was an internal frame system with lateral rods thus giving some adjustable dynamic characteristics. The internal frame pack and the shorter TV allowed better maneuverability and load control. The pack integrated well with the TV because specific interference problems were identified earlier in the process and corrected.

When the results were compared to the benchmark pool, the F model fell into the superior category on 48% of the variables, above average on 24%, below average on 14% and inferior on 14% of the variables. The pack was in the lowest 10% or inferior on amplitudes of forces and moments at the level of the hips. These amplitudes were being absorbed by the suspension system as neither the pack motion nor pressure at the shoulders were increased as a result of these increased amplitudes. Further human trials are needed to evaluate whether larger amplitudes of force and moments are problematic for the wearer.

All of these variables were validated against soldier input on wearing the LC systems [1, 8]. In comparison to proposed objective standards, the F model had less that 8 mm of absolute relative motion during walking and lower than 20 kPa of average pressure at the skin contact surface areas. Peak pressures were under the recommended 35 kPa with the highest peak pressure merely 27 kPa while carrying a 28.67 kg testing load. The final F model had good control in the relative pack to person motions, average suspension system stiffness, low average and peak pressures in the anterior and posterior shoulder regions, average forces and reaction moments but higher amplitudes of force and moments at the level of the hips. Overall this LC system would be a benchmark of standards that can be attained in future systems.

Overall Conclusions and Recommendations

Based on objective biomechanical testing, the F model was above average or superior to other LC systems in the database. It was concluded that this system should go forward to soldier field trials. It was also concluded that the objective assessment tools were cost and time effective and that they could provide designers with important feedback on the design characteristics of the system. Each design iteration would be tested and feedback given with two weeks. However, this scientific testing cannot replace human trials for critical design evaluations, especially in relation to pack features and functionality.

The new F model was recommended for field trials and was subsequently tested by many soldiers representing a range of military units. Since that time subtle design changes have been made in the CTS system more due to functionality than biomechanical performance. It is recommended that the final system be evaluated at Queen’s and treated as the new Canadian benchmark standard since some packs in the database are poorer than current ‘state of the art’ systems.

Several concepts and concerns still need to be addressed in future testing. For example, it is not known if dynamic suspension systems will improve the overall performance of a LC system. As well, basic scientific data need to be collected on acceptable skin contact pressures to determine maximum tissue tolerance limits for military procurement guidelines.

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Military Load Carriage: A Novel Method of Interface Pressure Analysis

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Summary

In the current military climate there is a constant need to strike a balance between the increasing amount of equipment carried by the modern soldier and the need to optimise performance and health. In co-operation with the Defence Clothing and Textile Agency, load carriage equipment has been developed making use of novel interface materials. These are used to distribute interface contact areas more extensively yet maintain air space next to the body surface. The purpose is to minimise peak pressure zones and reduce discomfort and pain so as to optimise performance and reduce the opportunity for injury. The paper will present novel methods for analysing interface pressures measured during load carriage on a treadmill and will consider the efficacy of this brief, evaluative technique.

Introduction

Throughout history man has been dependent upon the manual carriage of loads for purposes of survival, migration and warfare. Although modern technologies have managed to liberate him from this in many situations, there are still many occupational tasks, which require the carriage of heavy loads over long time periods. Foot soldiers are often required to carry heavy loads over much longer distances than any civilian counterpart. As the loads carried by soldiers have risen considerably over time so has the amount of research conducted into this area, with the aim of making the foot soldier more effective in terms of how much they can carry and for how long they can carry it.

The majority of the early work carried out in this area has concentrated on the physiological and specifically the cardio-respiratory effects of load carriage and the results of this are well established (Datta and Ramanathan, 1971; Datta et al., 1973; Epstein et al., 1988; Patton et al., 1989; Holewijn, 1990; Lind and McNicol, 1968). More recently however, the emphasis has shifted towards a more ergonomic, user-centred approach and has started to look towards making improvements to reduce the overall strain on the soldier. This work has included attempts to utilise the areas of the body most suited to the carriage of heavy loads with the aim of improving user comfort and health. A large part of the recent work in this area has been carried out by the Ergonomics Research Group at Queens University, who have developed a comprehensive suite of biomechanical tools for evaluating load carriage systems (Doan et al., 1998; Johnson et al., 1998; Rigby et al., 1998). As part of this work, they have been investigating the effects of carried loads on interface pressures and have developed an extension methodology using the Tekscan pressure measurement system (Bryant et al., 1996; Stevenson et al., 1995 and 1996.)

This work has concentrated on the effect of Load Carriage Systems on interface pressure and used only human participants, a method that has not been extensively studied before. The aim of this work was to develop an objective methodology, which, along with participant ratings of comfort, will allow reliable and repeatable comparisons of load carriage systems. New interface materials were evaluated, in terms of their ability to effectively distribute pressure, in order to prevent user pain and discomfort, the precursors to damage, injury and loss of performance.

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The aim of the first experiment was to evaluate an air mesh material which has been found to increase the evaporative heat loss from the body when exercising in a hot climate (Martin and Hooper, 1999). Due to the nature of this material, it may increase pressure distribution and improve user comfort. It was compared directly with the current in-service backpack of the British military, which incorporates 90-pattern foam at the interface.

The aim of experiments 2,3 and 4 was to look at a large number of different designs of shoulder straps in order to examine the effects on comfort and pressure distribution. The designs varied in width and interface material, which included foams, air meshes and plastics. The first goal was to select a smaller number of prototype straps for a further, more comprehensive evaluation involving a much larger sample.
Experiment 5 investigated different designs of backpack belts, their effect on shoulder pressures and overall pressure distribution, different interface materials and body location.

Methods

In total, 38 healthy participants (41 male, 31 female) participated in five experiments under conditions approved by the Ethical Advisory Committee of Loughborough University. The participants had a (mean ± SD) age of 22.35 ± 2.89 years, weight of 68.27 ± 7.5 kg, height of 174.72 ± 7.84 cm, and B.M.I of 22.3 ± 1.5 kg/m^2. Prior to participation participants completed and signed a form of consent.

One military rucksack was used in all the studies. This pack had changeable shoulder straps and hip belts allowing the conditions to be changed whilst keeping the load properties the same. The rucksack was kept at a standard load of 20kg. During the trials, the participants wore training shoes, cotton tracksuit trousers and cotton T-shirt. No participant took part in more than one of the experiments. The rucksacks were donned and fitted to the stipulation of the experimenter, providing consistency of fit. The participants were then permitted to re-adjust the tension to suit their own preferences.

Each trial lasted of 30 minutes treadmill walking at a speed of 3.5km/h whilst carrying the pack under investigation. The trials were held at the same time of day for each participant and the order in which the packs were carried was randomised. All of the trials were separated by at least a week.

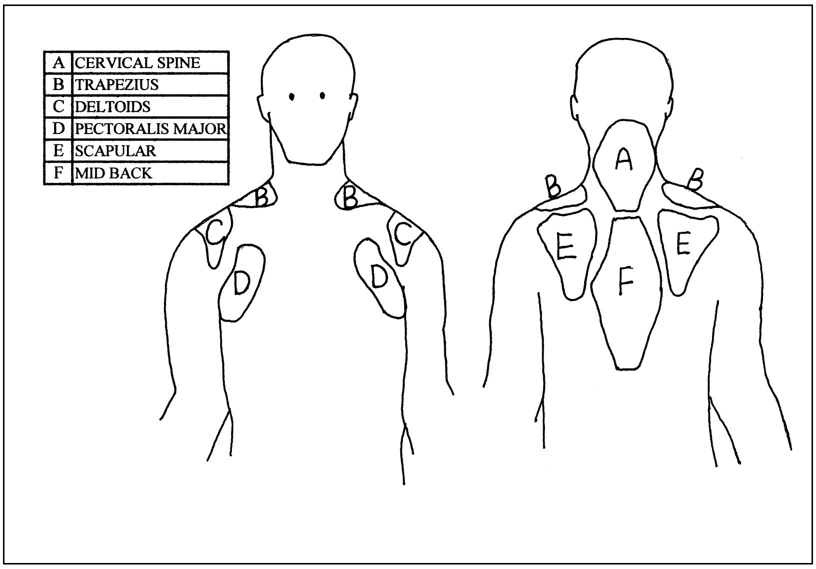
Whilst completing the trials, shoulder pressure was measured using the Tekscan™ system. An F-scan sensor was used consisting of 952 individual sensels over the shoulder area. In addition, in experiment 5 interface pressure at the hip area was also measured.

Before the trials, the sensors were equilibrated and calibrated in a pressure bladder. In order to ensure the same placement of the sensors in all conditions the real time monitoring of the Tekscan software was used. One of the individual sensels was matched with a certain anatomical landmark on the participant's body. For example in the case of one of the participants sensel 34, 19 (row, column) was matched up with the superior aspect of the left clavicle, 4cm from the sternal end, and sensel 34, 3 was matched up with the inferior aspect of the clavicle, 14 cm from the sternal end.

Repeatability of the pressure measurements was assessed by a test - re-test study of 5 participants. Each participant attended the lab on two different occasions and was measured carrying the same backpack, which were fitted as detailed above. The same calibration process was used on both occasions but a different sensor was used for each occasion. Out of a total out of 723 individual pressure readings (greater than zero), 92.51% (669) were found to be identical, 5.67% (41) were within 1% of the original reading, 1.67% (12) were within 5% and 0.15% (1) was within 10%.

During the trial, pressure readings were taken at 5-minute intervals, 10 frames over a 0.5-second time period were recorded starting at left heel strike. Prior to experimentation, pressure throughout the gait cycle was examined and this was found to be the point where pressure was the highest. The pressure sensors were split into six zones for the purpose of analysis, participants were asked to rate their comfort underneath the pack at six areas over the shoulder area as displayed on a body map (figure 1). The scale ranged from 1 - 5, with 1 being ‘comfortable’ and 5 being ‘unbearably uncomfortable’.

Figure 1. Body Map showing the six shoulder zones



Indices of pressure distribution:

Mean overall pressure	Total force exerted on the sensor divided by the number of individual sensing cells
Mean top 120 sensels	The mean of the highest 20 (12%) individual sensing cells in each ‘zone’ of the sensor.
Maximum pressure	The single highest recorded pressure on the sensor
Contact Area	The area of the sensor with recorded pressure

Paired t-tests and repeated Analysis of Variance tests were used to determine statistical variance in pressure between conditions. The Wilcoxin matched-pairs signed ranks test was used to assess the significance of difference between the ratings of perceived general comfort given by participants. Statistical significance was accepted at the 0.05 level. Reported results are means ± SD.

Results

Experiment 1 – Comparison of an air mesh material at the body interface with the in-service 90 Pattern foam.

The overall pressures underneath the shoulder straps in each condition were not found to be significantly different, as the designs of the pack and mass location were identical with only the interface material differing between the packs. This allowed comparisons between the conditions to be made, as the loads in each case were the same (Table 1).

Table 1. Differences in mean pressure distribution between air mesh pack and standard pack (n= 18)

	Air Mesh Interface	90 Patt. Foam Interface
Overall mean pressure (kPa)	7.08 ± 0.63	6.09 ± 0.44
Mean of top 120 senses (kPa)	19.5 ± 1.57	29.5 ± 1.94 *
maximum pressure (kPa)	78.2 ± 18.0	115.8 ± 29.1 *
Mean comfort rating	3.29 ± 0.72	4.55 ± 0.77 *

* difference significant at p = < 0.05 level

When the pressure distributions are examined however, it can be seen from the highest 120 (12%) individual pressure readings that the air mesh interface reduces the value of these by around a third, from 29.5k Pa to 19.5 kPa. This is also illustrated by the reduced mean maximum pressure of 78.2 kPa compared with 115.8 kPa for the standard interface material. The air mesh pack appears to take the same load and distribute it more evenly over the body surface, resulting in less pressure hot spots. It would appear that participants are sensitive to this change in pressure distribution as they consistently rated the air mesh more comfortable than the standard pack after carrying both for 30 minutes. The average comfort rating was 3.29, between uncomfortable and very uncomfortable, compared with 4.55, between very uncomfortable and unbearably uncomfortable for the standard pack.

Experiment 2 – Comparison of four different 90 pattern foam shoulder straps; standard (A), narrower (B), wider (C) and with plastic insert (D).

Again, the differences in overall shoulder pressures were found to be non-significant (table 2). The means of the highest 12% of sensels were not found to differ significantly when the thickness of the straps were varied, although the narrower 90 pattern strap was found to result in slightly higher readings. The maximum pressures support this, the wider strap does not appear to result in any difference from the standard pack with values very similar to the standard 90 pattern strap, however the narrower strap results in higher pressures.

Table 2. Effect on pressure distribution of 90 pattern foam (n=5)

	Standard	Narrower	Wider	Plastic Ins.
Overall mean pressure (kPa)	4.3 ± 1.2	5.0 ± 0.9	4.8 ± 1.1	5.1 ± 0.9
Mean of top 120 sensels (kPa)	20.4 ± 5.1	25.5 ± 4.1	19.6 ± 5.4	8.2 ± 0.6 *
maximum pressure (kPa)	99.8 ± 5.6	117.8 ± 6.6*	94.2 ± 10.2	78.8 + 5.3 *
contact area (cm^2)	38.2 ± 8.1	25.4 ± 6.2	31.4 ± 7.8	47.7 ± 4.3 *
Mean comfort rating	3.78 ± 0.6	4.33 ± 0.7*	3.82 ± 0.5	3.55 ± 0.6

* significant difference found between the other three conditions (p = < 0.05 level)

Adding a plastic insert does have an effect on pressure distribution when compared with the identical strap without plastic. The mean of the highest 120 sensels was 8.2kPa, significantly lower than 20.4kPa underneath the standard strap. The maximum pressures are also reduced to a mean of 78.8kPa compared with 99.8kPa. Adding the plastic insert distributes pressure more effectively by increasing the surface area of the body used for pressure distribution, the contact surface area increasing from 38.2cm^2 underneath the standard strap to 47.7cm^2 when the plastic is added. Again, these objective variables are supported by the ratings of the participants, the strap incorporating the plastic insert being rated lower than the standard strap, 3.55 compared with 3.78. The participants rated the wider shoulder strap very similarly to the standard pack, although the narrower strap was rated significantly less comfortable than the other three belts, again backing up the objective data.

Experiment 3 – Comparison of four shoulder straps consisting of three different air Meshes (E, H, and J) and one with mesh J with added plastic (I).

The overall mean pressure exerted on the shoulder in all four conditions was the same (table 3). In this experiment Strap E consisted of the air mesh material found to be effective in aiding evaporative heat loss in hot environments, and also more effective at distributing pressure over the shoulder area (experiment. 1). It can be seen that strap H, which consisted of a different air mesh material, was more effective than the mesh E at distributing pressure: resulting in a lower mean maximum pressure of 71.2 kPa, and a significantly lower mean of the highest 120 pressures (17.8 kPa). Again the mechanism for this appears to be the greater surface area of the shoulder being used for pressure distribution. Strap J, which consisted of another air mesh material, performed very similarly to strap E.

Table 3. Effect on mesh type and plastic insert on pressure distribution (n=5)

	E	H	I	J
Overall mean pressure (kPa)	5.2 ± 1.7	4.9 ± 0.6	5.4 ± 1.2	5.1 ± 0.9
maximum pressure (kPa)	78.2 ± 6.5	71.2 ± 4.4	84.4 ± 9.8	82.4 ± 8.1
Mean of top 120 sensels (kPa)	24.8 ± 4.2	17.8 ± 3.3*	26.3 ± 2.4	25.2 ± 6.7
contact area (cm^2)	25.1 ± 3.2	32.4 ± 7.1*	17.4 ± 4.3*	24.8 ± 6.3
Mean comfort rating	3.2 ± 0.7	3.1 ± 0.4	3.3± 0.5	3.3 ± 0.6

* significant difference found between the other three conditions (p = < 0.05 level)

It would appear that adding a plastic insert to the mesh of strap J, to make strap I, does not result in a further reduction in shoulder pressures. When comparing the pressure indices of straps I and J, it can be seen that adding plastic increases the mean maximum pressures and the mean of the highest 120 sensels cells, although these differences are not statistically significant. This indicates that adding a rigid plastic to an interface material may not always have a beneficial effect on pressure distribution,

Experiment 4 – Comparison of four shoulder straps consisting of three different air Meshes (M, N, and Q) and one with mesh Q with added plastic (O).

All of these meshes performed well with maximum pressures lower than the standard 90-pattern foam. Out of the 3 mesh straps without plastic inserts (M, N and Q) it is Q that performs best with the lowest mean maximum pressure, 58.4 kPa compared with 70.8 kPa for M and 81.8 kPa for N. It also has a high contact area used for pressure distribution, 90.2cm^2 compared with 90.4cm^2 (N) and 77cm^2 (M). The performance in terms of pressure distribution of the mesh used in strap Q is further enhanced when a plastic insert is added (strap O). This plastic insert results in a lower mean maximum pressure (43.8kPa) and a lower mean of the top 12% of pressures (16.6 kPa). Adding plastic increases body contact surface area still further to 96.7 cm2. Out of these 4 straps the participants rated O as the most comfortable, closely followed by Q, 2.78 and 2.99 respectively, although straps M and N were also rated well, 3.0 and 3.2.

Table 4. Effect of mesh type on pressure distribution (n=5)

	Mesh 'M'	Mesh 'N'	Mesh 'O'	Mesh 'Q'
Overall mean pressure (kPa)	4.8 ± 0.9	5.3 ± 1.1	5.4 ± 0.8	5.5 ± 1.0
maximum pressure (kPa)	70.8 ± 19.3	81.8 ± 6.2	43.8 ± 9.0*	58.4 ± 5.2 *
Mean of top 120 sensels (kPa)	20.8 ± 7.1	28.8 ± 6.6	16.6 ± 3.5*	23.2 ± 1.6 *
contact area (cm^2)	77.2 ± 7.1*	90.4 ± 3.7	96.7 ± 8.4	90.2 ± 3.2
Mean comfort rating	3.0 ± 0.9	3.2 ± 0.7	2.8 ± 0.5	3.0 ± 0.5

* significant difference found between the other three conditions (p = < 0.05 level)

Experiment 5 – Influence of backpack belts on shoulder and hip pressures. Comparison of different interface materials and placement**,** 90 Pattern foam belts at waist and hip level (1 and 2), air mesh shown to have thermal benefits with added plastic (3) and two new air meshes with plastic inserts (4 and 5).

The most important consideration when evaluating the performance of a backpack belt is how effective it is in reducing shoulder pressure. Out of the 5 belts under investigation, belt 1 resulted in the smallest reduction in shoulder pressure, 8.7%. This belt was the current 90-pattern foam belt and was situated around the participant’s waist. Belts 2, 3, 4 and 5, which were situated around the hips, reduced shoulder pressure by 48.3%, 42%, 41.4% and 39.2% respectively. It is therefore clear that placement around the hips is a necessity for good displacement of load from the shoulders.

Table 5. Effect of Belt Design on mean pressure distribution at the hips (n=5)

	1	2	3	4	5
%reduction in shoulder pres s.	8.7± 4.2*	48.3 ± 6.2	42 ± 8.3	41.4 ± 12.3	39.2 ± 14.2
Mean overall pressure (kPa)	3.2 ± 1.4	2.9 ± 0.6	4.6 ± 0.4	3.68 ± 1.0	1.7 ± 0.6
maximum pressure (kPa)	139 ± 12.0*	82 ± 8.3	88 ± 14.9	79 ± 5.2	57 ± 17.1*
Mean of top 120 cells (kPa)	25.6 ± 5.7	19.7 ± 5.2	26.9 ± 5.1	27.1 ± 3.7	16.3 ± 2.6
contact area (cm^2)	21.3 ± 3.2	23.1 ± 7.4	25.5 ± 4.5	21.3 ± 3.3	26.8 ± 7.4
comfort rating (shoulder)	2.85 ± 0.8	2.65 ± 0.6	2.58 ± 0.7	2.61 ± 0.4	2.57 ± 0.3
comfort rating (hip)	2.30 ± 0.4	2.22 ± 0.5	2.08 ± 0.6	1.98 ± 0.3	2.13 ± 0.5

* significant difference found between the other three conditions ($p = < 0.05$ level)

There was no significant difference in the reduction of shoulder pressure between the four hip belts. However, a reduction of shoulder pressure results from passing a proportion of the load amplitude or spread to the hips (or waist). A change in the pressure footprint (scale/area or both) under the belt must result. Therefore the issue of how well this pressure is distributed at the hips may be the deciding factor in the choice of a belt. Hip belt 5 results in the lowest mean maximum pressure of 55 kPa and also results in the best shoulder ratings of comfort, 2.57. The small differences in ratings of hip comfort for the four hip belts indicate that the participants are less sensitive to differences in pressure in this area, as is to be expected due to the difference in anatomy of this area when compared with the shoulder area. It may be the case therefore that the choice of an interface material should be based on its ability to reduce shoulder pressure and increase shoulder comfort rather than optimising hip comfort.

Conclusions

Methodological

In conclusion, a reliable and repeatable laboratory tool has been developed, which is sensitive to design differences between load carriage systems, and which produces results which agree with participants ratings of perceived comfort. However, a lot of work has still to be carried out regarding the absolute values of these pressure measurements. This will be required in order to make conclusions regarding acceptable limits at the interface. It should be pointed out that in this paper measurements have been taken at the point in the gait cycle where interface pressure is at its greatest. In addition, the next step of this work is to attempt to modify this tool for use in the field, allowing measurements to be made over different terrain and in different environments.

Design

From this work, a number of recommendations can be made, although final prototype testing and field trials are required to confirm these. Improvements in pressure distribution and user comfort can be achieved by altering the interface material of a backpack. The mechanism is to effectively distribute pressure, thereby reducing higher pressures, which are likely to lead to discomfort and may eventually lead to pain and loss of function.

One material that has been found to do this is monofillament air mesh, and this also has the benefit of enabling soldiers to lose excess heat. However, other mesh types may improve pressure distribution still further and these need to be investigated in future work. The majority of the meshes investigated in this work perform better than the standard foam currently used as the interface material for British military backpacks.

The use of a plastic insert to an interface material may improve pressure distribution by increasing still the surface area of the body used for pressure distribution, resulting in lower pressures. However, it has been shown that this may not be the case for every interface material and comprehensive work must be undertaken in order to confirm this.

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Accuracy of the Iscan Pressure Measurement System

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Summary

The Iscan system can be used to measure continuously changing force and pressure distribution at biomechanical interfaces. The objective of this study was to determine how accurately the Iscan system measures force and force distribution in static loading. Known absolute and relative loads were applied to Iscan sensors using custom-built indentors loaded in a servohydraulic test machine. Over the 35 trials, the mean error for the absolute measurement of force was 6.5% and the standard deviation of the error was 4.4%. The mean error in the force distribution measurement over the 25 trials was 0.86 % and the standard deviation of the error was 0.58%. The results suggest that, when calibration, conditioning and testing protocols are developed carefully, the Iscan system measures force and pressure distribution more accurately than Fuji Prescale film.

Introduction

The transmission of load across biomechanical interfaces has been studied by making measurements in cadaver specimens and mannequins loaded to simulate *in vivo* mechanics. Fuji Prescale film (Fuji, Tokyo, Japan) has been used extensively to measure contact area and pressure, from which resultant load can be determined. This transducer is limited because only the peak pressure and total area are recorded for a given load cycle.

The Iscan system (Tekscan, Boston, MA) makes dynamic measurements of pressure, force and area. The system consists of a 0.1 mm thick, flexible printed circuit sensor, an interface to a personal computer and data analysis and acquisition software. Although some performance features of the system have been assessed under certain conditions [1,2,3], the system's accuracy has not been characterized completely.

The objective of this study was to determine how accurately the Iscan system measures force and force distribution in static loading.

Methods

In all tests, the Iscan sensor was loaded in a servohydraulic testing machine (Instron 1331, Canton, MA) between sheets of 1/8" thick rubber backed on the bottom with a machined aluminum base and on the top with one of several machined aluminum indentors. Both sides of the Tekscan sensor were lubricated with water and surgical jelly to reduce shear. In all tests, a 5 s long ramp function increased the load to the desired value, where it was then held for 5 s, at which point the force measurement was recorded. Applied force was measured with a calibrated load cell (Sensotec).

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Each Iscan sensor was conditioned and calibrated using a flat aluminum indentor that covered the sensor completely. The sensor was conditioned by loading it to 2.1 kN (120% of the maximum expected applied force) five times. The system was calibrated, using its preprogrammed two-point calibration routine, at 0.35 and 1.4 kN (loads corresponding to 20% and 80% of the maximum expected load).

Force accuracy was assessed by applying loads at 7 levels corresponding to mean pressures of 1-7 MPa through a flat-ended cylindrical indentor (266 mm^2). Five trials were performed at each load level. Accuracy was quantified by the mean absolute difference between the Iscan measurement of force and force measured with a calibrated load cell.

Force distribution accuracy was assessed by applying a resultant load of 1000 N through two flat-ended cylindrical indentors (123 mm^2) using a linkage to distribute the resultant force between the two at 5 known ratios. Five trials were performed at each load ratio. Accuracy in the relative distribution of force was defined as the difference between the applied higher force (calculated from the load cell measurement and the geometry of the linkage) and the Iscan measurement of higher force.

Results

Over the 35 trials, the mean error for the absolute measurement of force was 6.5% and the standard deviation of the error was 4.4 %. No relationship between applied force and measurement accuracy was evident (Figure 1).

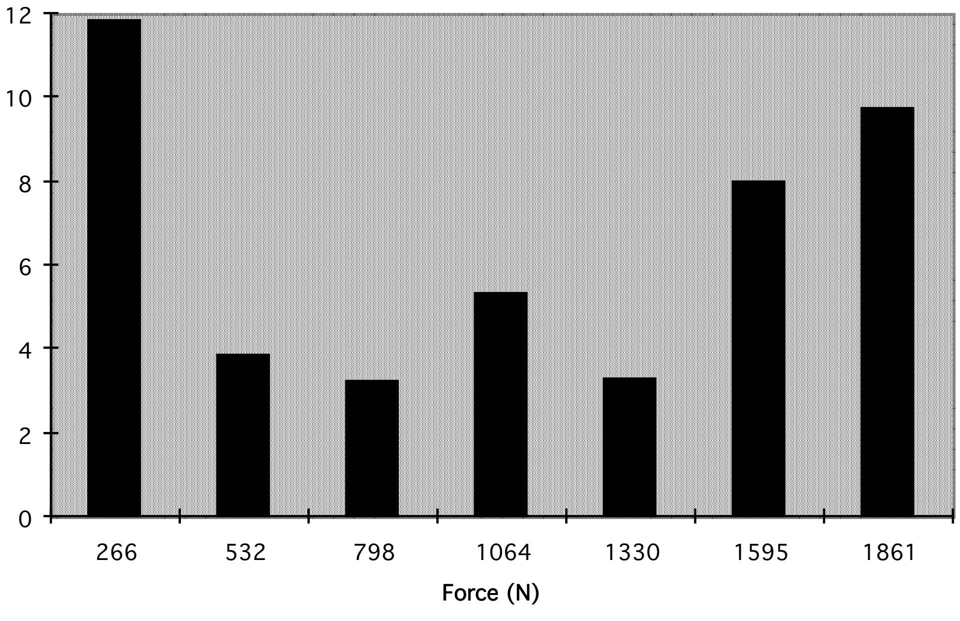

Figure 1. Error in force measurement (average of 5 trials)

The mean error in the force distribution measurement over the 25 trials was 0.86% and the standard deviation of the error was 0.58%. No relationship between applied force and measurement accuracy was evident (Figure 2).

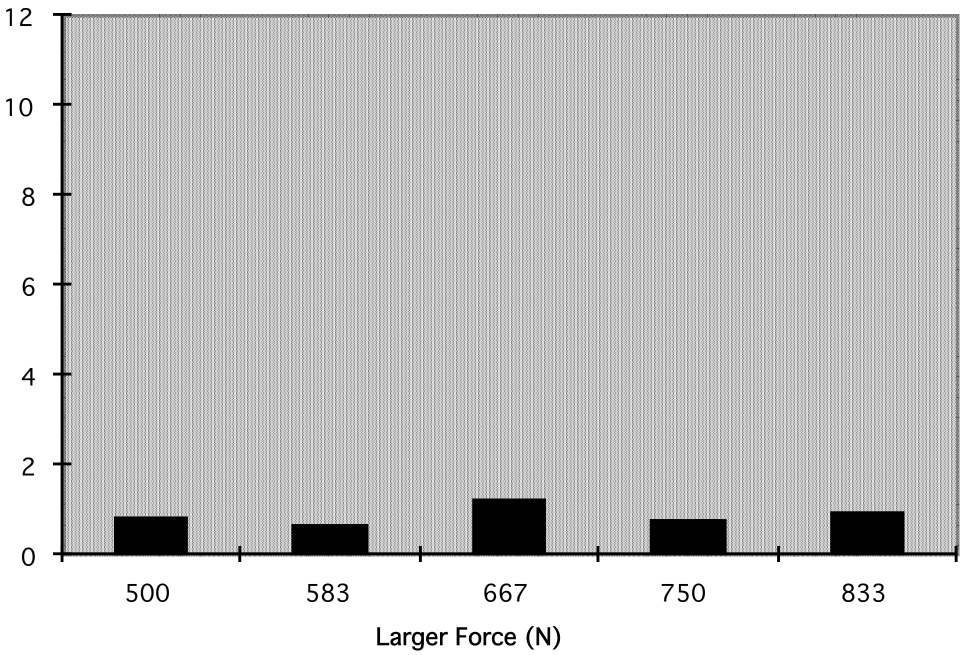

Figure 2. Error in force distribution measurement (average of 5 trials)

Discussion

Based on these results for the accuracy of force measurements and earlier calculations of the accuracy of Iscan area measurements (3%) [2], we conclude that the accuracy of the Iscan system's prediction of mean pressure is better than Fuji Film's (commonly acknowledged to be 10%).

The high accuracy of relative force distribution measurements makes the Iscan system useful in many biomechanical applications. The system can be used to study small changes in contact pressure and force distribution that could not be discerned by Fuji Film. In many applications it is more important to measure the change in contact pressure or force distribution than the absolute contact pressure or force.

It is important to note that the tests performed have been designed to minimize the effects of drift and hysteresis that the Iscan system displays [3], and that the accuracy with which the system measures a changing dynamic load may be substantially poorer than the static accuracy measured. One limitation of our study is that, although the compliance of a human diarthrodial joint has been approximated in these tests, the system may display different characteristics when measuring within the asymmetrical geometry and changing compliance of human joints and synthetic-human interfaces.

The Iscan system offers several advantages over Fuji Film: dynamic measurements can be made, the sensor is thinner and therefore interferes less with normal contact mechanics, and data acquisition and analysis is straightforward. Because Iscan's performance is comparable to Fuji Film's, it should be considered a valid means for measuring contact forces and force distributions at biomechanical interfaces.

Acknowledgements

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Calibration Issues of Tekscan Systems For Human Pressure Assessment

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Summary

The Tekscan pressure sensor system has been designed for relatively easy measurement of contact pressures between two opposing surfaces. However, several factors are known to affect Tekscan sensor output. This paper reports on two pilot studies which were done to investigate the effects of contact surface compliance and changes in the system hardware on Tekscan sensor output. In the first study, linear calibration curves were calculated for a single Tekscan sensor array placed on surfaces of varying compliance. The slopes of the curves and variability in both the slopes and intercepts were found to be affected by surface compliance. In the second study, absolute percentage differences in the raw output data bits between a series of Tekscan sensor-cuff combinations were calculated. These differences ranged from 5-32%. The results of these studies indicate that careful attention must be paid to system set-up and calibration when using the Tekscan pressure sensor system to measure contact pressures.

Introduction

An important measure in load carriage studies is the contact pressure experienced by a bearer under the load carriage elements. Previous studies have identified pressure thresholds beyond which there is an increased risk of injury (Holewijn, 1990). Tekscan Inc.[1] has developed a tactile force sensor based on the use of conductive or semi-conductive inks sandwiched between thin, flexible polyester sheets. Electrically conductive pathways are imprinted on the polyester sheets and the conductive ink is deposited between the upper and lower sheets at locations at which the pathways intersect. The ink provides an electrical connection between the upper and lower conductors. The resistance of this connection changes with an applied compressive force. Thus, the Tekscan sensor array comprises a grid of force sensing elements (sensels) which are electrically isolated from each other. Knowing the spatial dimensions and separation of the sensels, the measured force data can be converted into a pressure profile. By varying the spacing and patterns of the conductive pathways, Tekscan has produced an array of sensors of various shapes, sizes and sensel resolution.

The Tekscan pressure measurement system offers a convenient method for measuring contact pressures between two opposing surfaces. The sensors are very thin and flexible and will conform to contoured surfaces. The system is supplied with dedicated hardware and software to measure the change in resistance with applied force across sensels, digitize the measured signals, transfer the digital data to PC and display the measured data as a dynamic pressure profile. In comparison with other contact pressure measurement systems, it is relatively cost-effective. For these reasons, the Tekscan system was adopted by the Ergonomics Research Group, Queen's University, to measure contact pressures under load carriage elements on the Load Carriage Simulator (Bossi et al., 2000). However, there are several factors which are known to affect Tekscan sensor output and, consequently, the accuracy of the reported pressure measurement. These factors include: variations in sensitivity across individual sensels; creep in the output with constant applied pressure over time, leading to hysteresis in the dynamic response; temperature; contact surface curvature; contact

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[1] Information on Tekscan products can be obtained at www.tekscan.com.

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surface compliance and noise introduced by the system hardware (Bryant et al., 1999; Luo et al., 1998; Sumiya et al., 1998; Woodburn and Helliwell, 1996; McNeil, 1996).

This paper reports on two studies, which were done to investigate the effects of the last two factors on the measured output and calculated calibration curves of specific Tekscan sensor arrays. In the first study, calibration of the same Tekscan 9811 sensor array was performed with the array placed on surfaces of varying compliance. In the second study, F-scan sensor output was measured for several sensor-cuff combinations and for the sensors connected to the cuff in the normal and inverted orientations.

Methodology

The Influence of Contact Surface Compliance

Calibration curves were calculated for a single Tekscan 9811 sensor. The sensor comprises 96 sensels arranged in a 16×6 rectangular grid. Sensels are spaced 12.7 mm apart; the active area of each sensel is the 6mm × 7mm region in the centre of the effective sensel area, which is 12.7mm × 12.7mm or 161 mm^2. The dynamic range of the 9811 sensor is 1-500kPa.

Calibrations were performed using two calibrators: a flat, bladder calibrator and a hand-held calibrator. The flat bladder calibrator is comprised of two metal plates. The lower plate is covered in latex rubber and the Tekscan sensor array is laid over this plate. An inflatable latex rubber bladder is placed over the Tekscan array, such that it covers the entire array, and the upper plate is secured over the bladder. Constant pressure is applied across all sensels by inflating the bladder. The pressure level is read on the attached gauge. The hand-held calibrator (Bryant et al., 1999) applies a controlled force at the tips of four variable displacement pistons. The applied force is linearly related to a known pressure applied to the pistons. The centre-to-centre spacing of the pistons is the same as the sensel spacing in the 9811 sensor. The tips of the pistons are rounded to avoid edge effects. The hand-held calibrator activates four sensels at a time, and is moved across the sensor to calibrate the entire array.

The 9811 sensor was calibrated under four conditions:

- using the flat bladder calibrator;
- using the hand-held calibrator with the sensor array on a flat, non-compliant surface – the base of the flat bladder calibrator;
- using the hand-held calibrator with the sensor array on a relatively flat, slightly compliant surface – the back of the LC Simulator manikin, which is a rigid surface covered in Bocklite^{TM}, a skin analog;
- using the hand-held calibrator with the sensor array on a more compliant surface – the back of a human subject.

On the manikin and the human subject, the sensor array was positioned 3cm to the right of the spinal column, with the lower edge of the sensor at approximately T12. The sensor was activated at four pressures: 10, 20, 30 and 40 kPa using the flat bladder calibrator and 20, 30, 35 and 40 kPa using the hand-held calibrator. The raw output data bits were recorded for 10s at 1 Hz at each applied pressure to obtain ten 16×6 data arrays.

The recorded data were processed to obtain linear calibration curves for individual sensels under each of the four calibration conditions. The recorded output data bits were imported into Excel$^{®}$ and a single array for each pressure was obtained by averaging over the ten recorded arrays. Linear regression was performed across the four data points obtained for each sensel. A set of ninety-six separate calibration curves was obtained for each calibration condition. These curves were compared to assess the differences in the calibration of the 9811 sensor under the four separate conditions.

The Influence of the Tekscan Cuff

The F-scan in-shoe sensor was used in this study, since the F-scan sensor can be connected to the cuff in two orientations: normal and inverted, whereas the 9811 sensor can only be connected in one orientation. The F-scan sensor array contains 960 sensels arranged in a grid pattern with a spatial density of 4 sensels/cm^2. The dynamic range of the F-scan sensor is 1-150 psi (approximately 7-1000 kPa).

The F-scan sensor was placed in the flat bladder calibrator and connected to a Tekscan cuff in the normal orientation. A constant 40kPa pressure was applied and 21 frames of data were collected over 2s. The F-scan sensor connection was then inverted in the cuff and another 21 frames of data were collected. The procedure was repeated for two more F-scan sensors, using the same cuff and for the F-scan sensors using each of three different cuffs. The average absolute percentage difference was calculated for each pair of normal versus inverted output data bits and for output data bits collected from different sensor-cuff combinations. The absolute percentage difference was calculated using the absolute values of the differences in the output data bits.

Results

The Influence of Contact Surface Compliance

The slopes and intercepts of the linear calibration curves calculated for the individual sensels were averaged for each calibration condition. The averages, standard deviations and coefficients of variation are given in Table 1. The slopes for the individual calibration curves are plotted as bar graphs in Figure 1. It can be seen that the flat bladder calibrator gives the lowest calibration slopes and the lowest variation in the slopes. The average slope increases when the hand-held calibrator is used on the Tekscan sensor placed on the flat non-compliant surface. The slope decreases as the hand-held calibrator is used on more compliant surfaces, but the average slopes are still greater than the average slope for the flat bladder case. In all cases the average intercept is close to zero. As the surface compliance increases, the variability in both the slope and the intercept increases.

Table 1. Statistics for the slopes and intercepts[*] of the calibration curves calculated under the four calibration conditions

Calibration condition	**Slope**			**Intercept**		
	Average	Std. Dev.	Coeff. Var.	Average	Std. Dev.	Coeff. Var.
Flat bladder	0.243	0.036	0.148	0.43	0.804	1.87
Flat hand-held	0.331	0.085	0.257	-0.827	2.119	2.562
Manikin hand-held	0.289	0.115	0.398	-0.738	2.724	3.691
Human hand-held	0.262	0.165	0.630	0.249	4.526	18.177

[*] Slopes are in raw data bits/kPa; intercepts are in raw data bits

The calibration curves for each of the four conditions were used to calibrate a single pressure map obtained from a Tekscan 9811 sensor affixed to the mid-back of a human subject as the subject performed a range of motion task while wearing a loaded backpack. The resulting pressure maps are shown in Figure 2. The variability in reported pressure using the different calibration curves is obvious.

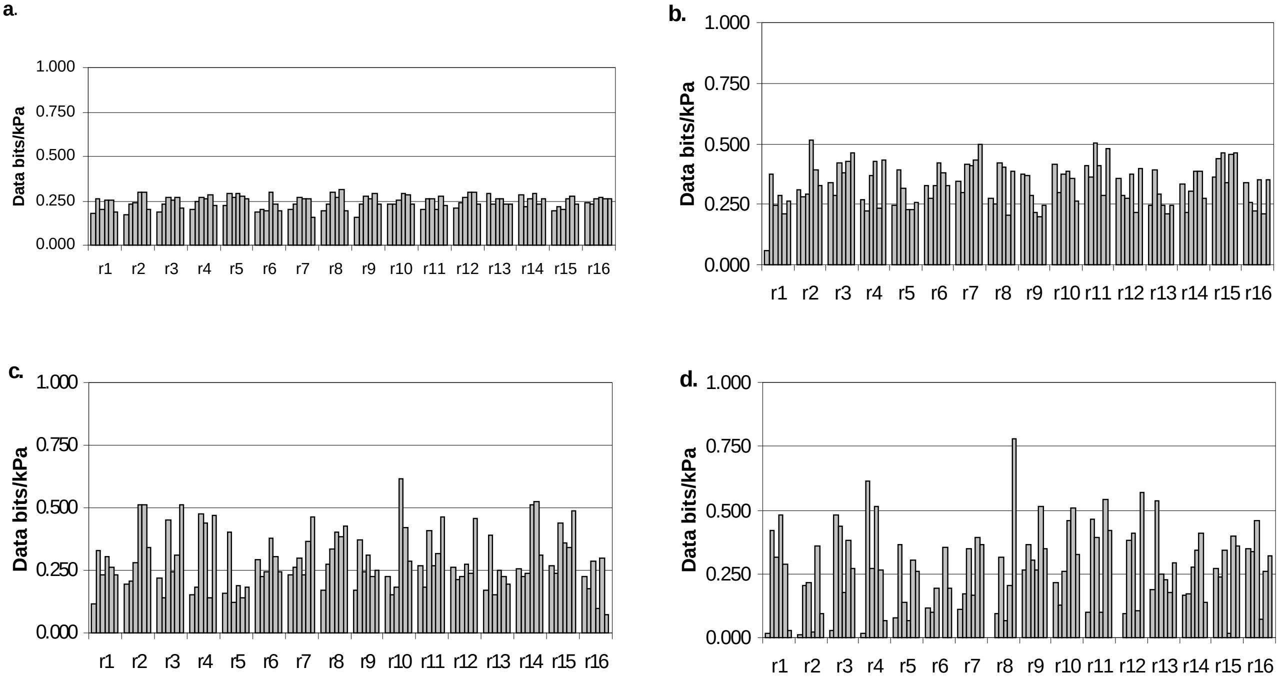

Figure 1. Linear calibration curve slopes for individual Tekscan sensels calibrated under four separate conditions: a. flat bladder calibrator; b. in-situ calibrator used on a non-compliant surface; c. in-situ calibrator used on a slightly compliant surface (the back of the LC manikin); d. in-situ calibrator used on a more compliant surface (the back of a human subject). r1 – r16 indicates row 1 to row 16; each row contains six sensels.

The Influence of the Tekscan Cuff

Table 2 summarizes the absolute percentage differences obtained for the various test conditions: normal versus inverted sensor-cuff orientation; changing cuffs; and changing sensors. In several cases, absolute percentage differences greater than 10% were obtained. In two cases, absolute percentage differences greater than 30% were obtained.

Table 2. Statistics for percent differences between F-scan data collected under different sensor-cuff orientations and combinations.

Condition		**Absolute Percent Difference**		
		Average	**Std. Dev.**	**Coeff. Var.**
Normal vs. Inverted Cuff Orientation		12.63	0.43	0.03
Changing FScan Cuffs (3)	Sensor 1	13.04	6.43	0.49
	Sensor 2	6.86	3.16	0.46
	Sensor 3	5.00	1.90	0.38
Changing FScan Sensor (4)	Cuff 1 (constant)	16.09	5.29	0.33
	Cuff 2 (constant)	15.14	3.26	0.22
	Cuff 3 (constant)	30.46	14.57	0.48
	Cuff 4 (constant)	32.69	17.25	0.53

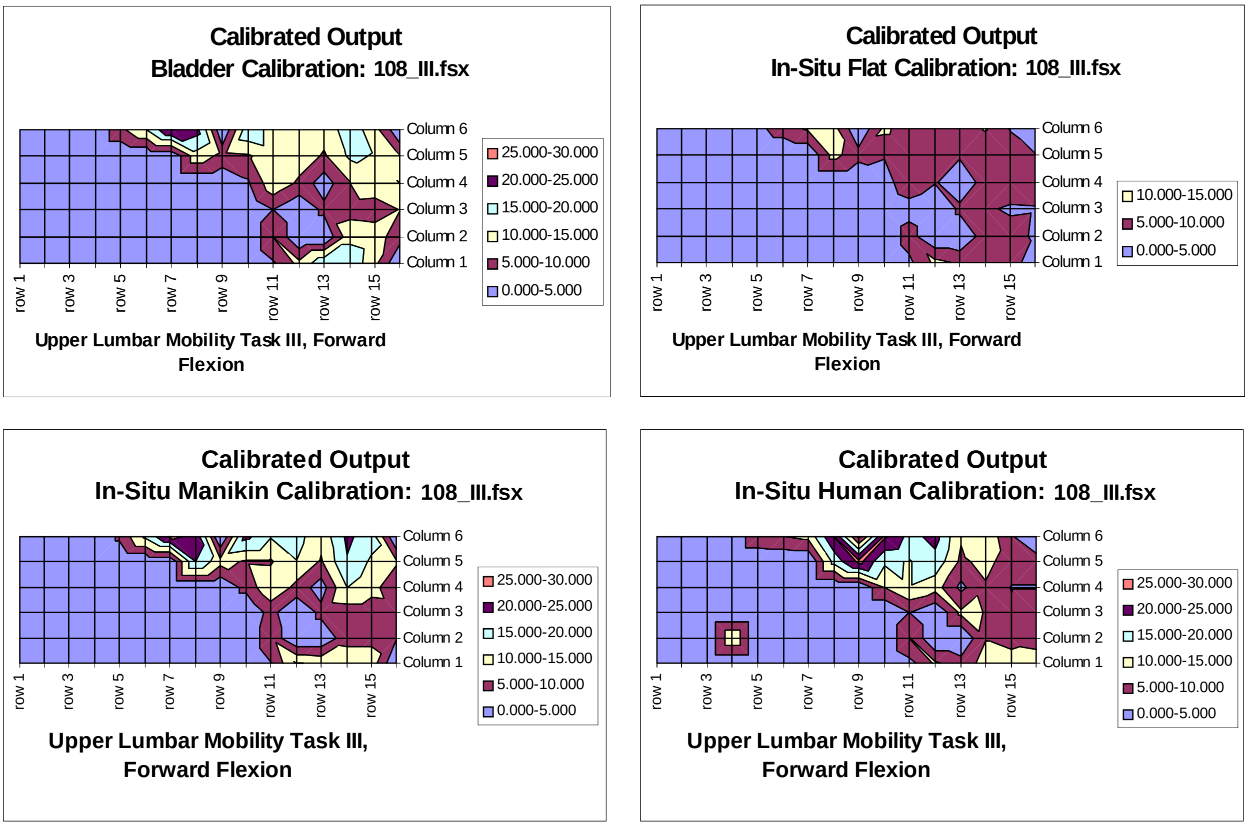

Figure 2. Tekscan pressure distribution maps for a single recording calibrated using each of the four sets of calibrations curves. The Tekscan sensor was affixed to the back of a human subject who was wearing a loaded backpack. The recording was made while the subject performed forward flexion at the hips.

Discussion

As noted above, the slope of the linear calibration curve decreases as the compliance of the surface under the Tekscan sensor increases, when using the hand-held calibrator. The lowest and most consistent calibration slopes, however, were obtained using the flat bladder calibrator, where a constant pressure was applied across all sensels.

Using the hand-held calibrator, calibration slopes and sensor outputs are lower for the Tekscan sensor located over more compliant surfaces. This agrees with results reported by Luo et al. (1998), who found that Tekscan sensor output increased with increased surface hardness. In our case, the decrease in sensor output can be, at least partially, explained by the fact that the compliant material under the Tekscan sensor and the sensor itself will deform under the piston when force is applied. Some of the reaction force under the piston, then, will occur around the curved edge of the contacting surface of the piston. This force will have a shear, as well as a compressive component, and the direct force experienced by the Tekscan sensel will be lower, hence a lower sensel output. It is important to recognize that a shear force component can exist in compliant material, and have an effect on the pressure measurement reported by Tekscan.

Luo et al. (1998) also reported that the pressure distribution recorded from the F-scan sensor was more uniform when pressure was applied over a softer surface. In the present study, however, the variation in the calibration slopes and output data bits across sensels was found to increase as the surface compliance increased. In Luo et al.'s study, an F-scan sensor was sandwiched between two surfaces, (configured as hard-hard, hard-soft and soft-soft), and a pressure of 193 kPa was applied uniformly over the sensor. This is quite different from the present study, in which a controlled force was applied to the central regions of four individual sensels using the hand-held calibrator. A compliant material under the sensor will deform with the applied force and because the sensor itself is flexible, it too will deform. The effect of such deformations on the Tekscan output is not well understood, but may be a source of inter-sensel variations. Another source of variability is the non-uniformity of the compliant surfaces. Neither the LC manikin nor the human provides a perfectly flat surface covered in a uniform thickness of compliant material. Variations in the surface contours and the Bocklite thickness on the manikin would contribute to variation in the Tekscan output. And in the human, variable compliance between regions supported by bone and those supported by soft tissues, results in variations in the pressure distribution across the surface.

Another source of variability in the reported results arises from the limited pressure range over which the Tekscan sensor was calibrated. Calibration data were recorded for pressures from 10 – 40 kPa. The Tekscan 9811/50/75 sensor has a dynamic range of 1 – 500 kPa. Working within a limited portion of the output range results in increased errors due to limited cell resolution (Luo et al., 1998). However, pressures experienced under well-designed load carriage elements (e.g. backpack shoulder straps and waistbelts) have been found to rarely exceed 40 kPa (Bryant et al.,1997). Calibration at these low pressures is important in applying Tekscan sensors to evaluate contact pressures experienced during load carriage.

In the second study reported here, it was found that reported pressures are affected by the hardware used (sensor array and cuff) and by the orientation of the connection between the sensor and the cuff for the F-scan sensor system. The absolute precentage differences obtained in this pilot study were found to range from 5-32%. These results attest to the importance of keeping the Tekscan set up consistent throughout the duration of an experiment.

The results of the two studies reported here indicate that the Tekscan sensor system must be carefully calibrated to obtain the best results in terms of accuracy and repeatability. Calibration should be performed under conditions that are as close as possible to the actual measurement conditions. Tekscan sensors have a limited lifetime and should be tested and replaced regularly. Tekscan cuffs should be put through regular maintenance cycles and re-calibrated after maintenance. The Tekscan sensor system has many advantages for use in measuring surface contact pressures. However, in the absence of a gold standard, accurate calibration of the Tekscan system remains a challenge and a good understanding of the factors which affect Tekscan sensor performance and contribute to variability in the output is essential.

Acknowledgement

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A Static Biomechanical Load Carriage Model

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Summary

A two-dimensional biomechanical model of a backpack has been developed which incorporates the primary forces at the shoulder and waistbelt contact points. The model had been validated using instrumented manikins in laboratory experiments. The computer-based formulation allows the user to specify parameters for certain pack features, such as pack mass and volume, and it predicts the resulting contact forces on the bearer. By treating some parameters as decision variables, such as the location of attachment of the shoulder straps to the pack, the model can be used as an optimization tool to achieve a specified objective, such as minimizing the total forces on the bearer. A base case analysis and some variants illustrate this type of analysis. For the example provided, it is not possible to find a feasible solution within the prescribed shoulder-to-waist load ratio. By freeing up other variables, several alternative solutions are presented. This model can be used to easily examine trade-offs in certain pack design decisions.

Introduction

Backpacks are common devices to increase human load carriage capabilities, but when heavily loaded can still place a great burden on the bearer. Many design improvements have been made over the past decades, but more research is still required to fully understand the implications of the associated static and dynamic forces. Parametric analysis of personal load carriage systems allows for increased understanding of relationships between system design characteristics and the impact of these design features on the bearer. A computer-based static biomechanical model of a backpack has been developed to represent the interaction between the pack and the bearer at the principal contact points.

Optimization of the biomechanical model yields the best location for attaching the suspension system components. Various objectives can be considered, such as achieving the best load balance between the shoulders and waist, or minimizing the transverse shear at the lumbar level, which is often associated with discomfort and pain. In the current formulation, the objective is to minimize the sum of the three primary forces acting on the bearer by the pack: the normal force at the shoulders, the vertical force on the hips and the lateral shear on the back at the wasitbelt. A limited set of runs applied to a Base Case backpack illustrates the trade-offs inherent in design decisions.

Literature Review

The literature on personal load carriage is quite broad, and generally falls into one of three categories: physiological studies, biomechanical studies, and subjective appraisal studies. Most of the biomechanical studies concentrate on gait analysis (e.g. DeVita et al., 1991). As there are several comprehensive survey articles on various aspects of load carriage (e.g. Rorke, 1990; Haisman, 1988; Pelot et al., 1995), the following review focuses on some articles directly relevant to the model described in this paper.

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Almost all studies consider the effects of load carriage on the subject through experimentation, and the backpack is part of the pack/person system. Articles examining the isolated pack as a system (static or dynamic) are almost non-existent, however Bobet and Norman (1984) develop a free-body diagram of the trunk/pack system while examining the effects of load placement using EMG. Furthermore, few studies concern themselves with load carriage design details. Exceptions include Bloom and Woodhull-McNeal (1987) who compare internal and external frame packs, and other researchers who consider a double-pack system (e.g. Kinoshita, 1985; Johnson et al., 1995). Certain pack elements are evaluated in isolation, such as the shoulder model presented by Holewijn (1990). Field trials comparing pack features are commonly reported in relevant magazines (e.g. Jenkins, 1992).

In order to establish limitations on contact forces, information is required on the effects of these pressures on the bearer. An article by Sanders et al. (1995) provides an overview of skin response to mechanical stress, while particular injuries arising from load carriage pressures are described in several articles (e.g. Bessen et al., 1987). Studies by Stevenson et al. (1996) have measured strap forces and pressures and correlated them with measures of human discomfort, thereby establishing threshold values on the force levels that may cause discomfort.

The body lean angle under load carriage depends on several factors including pack mass, pack design, level of fatigue, and terrain. Results of such investigations include those by Bloom et al. (1987) and Stevenson et al. (1996). Five to ten degrees is a typical range, but the user may specify this parameter in the model described in this paper.

Since the goal of this biomechanical model is to choose values for certain variables that will optimize an objective, such as minimizing total contact forces, the reader may consult a text such as Winston (1996) to review optimization and formulation in general, linear programming in particular, and non-linear programming, as some optional constraints in the present model introduce non-linear relationships.

Biomechanical Model

A free body diagram of a rigid model of a typical rucksack is shown in Figure 1. The notation is defined at Table 1. The suspension system elements have been numbered from the top down for convenience. Thus the upper shoulder strap's location (d_1), attachment angle (θ_1) and tension (T_1) are consistently subscripted. The subscript ‘2’ refers to the lower shoulder strap portion, and ‘3’ is reserved for certain waistbelt variables. The entire figure and its associated reference coordinates are angled at ß degrees from the vertical to reflect the normal body lean that occurs under heavy loading conditions.

When conducting a parametric analysis, many of the values in the diagram may be treated as variables, to determine the impact of changing them. For the evaluation of a specific pack under given loading conditions, all fixed parameters must be specified and the model is solved for the unknown forces T_1, T_2, F_Z and F_X. To solve for these using the three force balance equations, note that a relationship exists between T_1 and T_2. By modelling the shoulder as a pulley with friction, T_1 and T_2 are related by the friction coefficient and the wrap angle, as shown by equation (1) below (see MacNeil, 1996). The wrap angle α depends on several pack dimensions, notably the attachment points of the upper and lower shoulder straps, shoulder radius, and shoulder-pack distance, as shown in Figure 2 and equations (6) through (10).

Table 1. Notation for Static Biomechanical Model

Suspension System Element	**Notation**	**Definition**
Orientation	X	coordinate along pack depth (positive out)
	Z	coordinate along pack height (positive up)
Pack Container	W	the force of the mass of the pack
	v_X, v_Z	position of Centre of Mass
	h_X, h_Z	dimensions of pack container
Bearer	d_4	distance: waistbelt centre to shoulder centre
	d_5	distance: pack back to shoulder centre
	r	radius of shoulder
	r_H	radius of hips
	ß	body lean angle
	γ_1	anatomical lower back angle from vertical
	γ_2	anatomical hip angle from vertical
Waistbelt	T_3	tension in waistbelt
	d_3	distance of waistbelt from bottom of pack
	T_{3C}	compressive force that T_3 applies around the hips
	T_{3C}^N	component of T_{3C} normal to the hips
	T_{3Cf}	force of friction due to T_{3C}
	F^B_Z	lift provided by waistbelt resting on hips
	μ_B	coefficient of friction of waistbelt on hips
	t	thickness of waistbelt
	h_B	height of waistbelt
Shoulder Straps	T_1	tension in upper shoulder straps (LHS and RHS summed)
	T_2	tension in lower shoulder straps (LHS and RHS summed)
	d_1	distance: waistbelt centre to attachment point of upper shoulder strap
	d_2	distance from waistbelt centre to attachment point of lower shoulder strap
	θ_1	upper shoulder strap angle from pack normal
	θ_2	lower shoulder strap angle from pack normal
	α	angle subtended by contact of strap wrapped around shoulder
	μ_S	coefficient of friction of strap on shoulder
	S^N	net force acting normal to the shoulder
Lumbar area	F_X	reaction force of lower back on pack in X-direction
	F_X^N	component of F_X normal to the lower back
	F_{Xf}	force of friction due to F_X
	F^L_Z	lift on the pack from friction and angle at lower back
	μ_L	coefficient of friction of lumbar pad on lower back
	F_Z	total lift force at lumbar contact point of pack

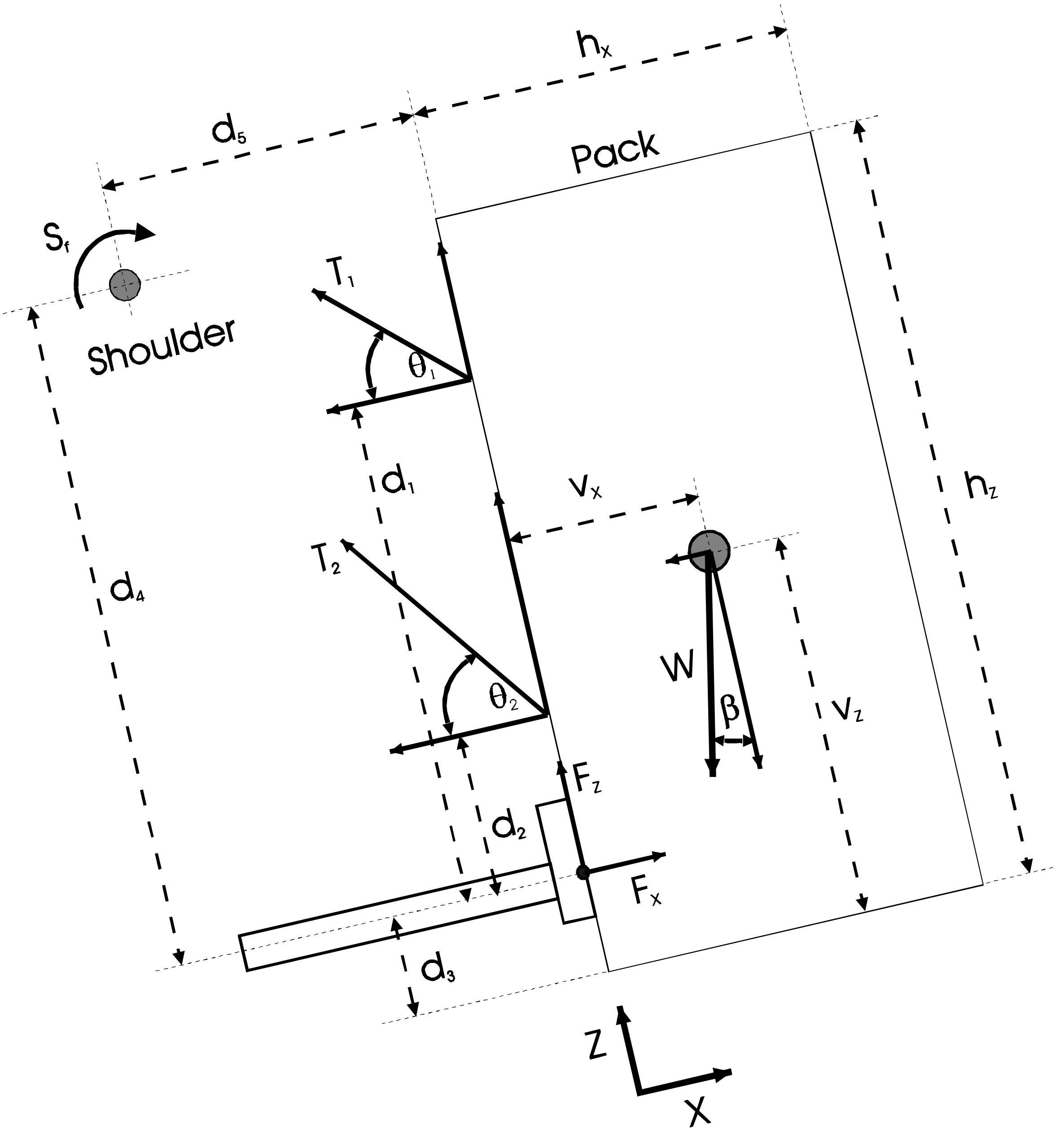

Figure 1. Rucksack free-body diagram with trunk lean

Equilibrium equations:

Pulley equation for shoulder wrap:

$$\frac{T_1}{T_2} = e^{\mu_S \alpha} \qquad \textbf{(1)}$$

Sum of the forces in the X-direction:

$$F_X = W \sin\beta + \left\{ e^{\mu_S \alpha} \cdot \cos\theta_1 + \cos\theta_2 \right\} \cdot T_2 \qquad \textbf{(2)}$$

Sum of the forces in the Z-direction:

$$F_Z = W \cos\beta - \left\{ e^{\mu_S \alpha} \cdot \sin\theta_1 + \sin\theta_2 \right\} \cdot T_2 \qquad \textbf{(3)}$$

Sum of the moments about the center of mass of the pack: **(4)**

$$\left\{ -(v_Z - d_2 - d_3) \cdot \cos\theta_2 - v_X \cdot \sin\theta_2 + e^{\mu_S \alpha} \cdot \left((d_1 + d_3 - v_Z) \cdot \cos\theta_1 - v_X \cdot \sin\theta_1 \right) \right\} \cdot T_2 + (v_Z - d_3) \cdot F_X - v_X \cdot F_Z = 0$$

Isolate T2 by substituting (2) and (3) into (4) and simplifying:

$$T_2 = \frac{W \cdot \left[v_X \cos\beta - (v_Z - d_3) \cdot \sin\beta \right]}{e^{\mu_S \alpha} \cdot d_1 \cdot \cos\theta_1 + d_2 \cdot \cos\theta_2} \qquad \textbf{(5)}$$

Shoulder Wrap angle:

$$\alpha = \pi + \theta_1 - \theta_2 \qquad \textbf{(6)}$$

$$\theta_1 = \tan^{-1}\left(\frac{e_1}{d_5} \right) \qquad \textbf{(7)}$$

$$e_1 = \frac{-2d_5^2 (d_4 - d_1) - 2d_5 r \sqrt{d_5^2 + (d_4 - d_1)^2 - r^2}}{2(r^2 - d_5^2)} \qquad \textbf{(8)}$$

$$\theta_2 = \tan^{-1}\left(\frac{e_2}{d_5} \right) \qquad \textbf{(9)}$$

$$e_2 = \frac{-2d_5^2 (d_4 - d_2) + 2d_5 r \sqrt{d_5^2 + (d_4 - d_2)^2 - r^2}}{2(r^2 - d_5^2)} \qquad \textbf{(10)}$$

Normal force on shoulders (sum of both sides):

$$S_X^N = T_2 \cdot e^{\mu_S \alpha} \cdot \cos\theta_1 + T_2 \cdot \cos\theta_2 \qquad \textbf{(11)}$$

$$S_Z^N = T_2 \cdot e^{\mu_S \alpha} \cdot \sin\theta_1 + T_2 \cdot \sin\theta_2 \qquad \textbf{(12)}$$

$$S^N = T_2 \sqrt{(\cos\theta_2 + e^{\mu_S \alpha} \cos\theta_1)^2 + (\sin\theta_2 + e^{\mu_S \alpha} \sin\theta_1)^2} \qquad \textbf{(13)}$$

Waist Belt Force:

Tension in belt vs. compressive force on hips, based on hoop stress: $T_3 = T_{3C} / (2\pi)$ **(14)**

Lift due to hip angle (i.e. cone effect) and friction: $F_Z^B = 2\pi T_3 \cdot \cos\gamma_2 \cdot (\sin\gamma_2 + \mu_B \cdot \cos\gamma_2)$ **(15)**

List due to lumbar pad: $F_Z^L = F_X \cdot \cos\gamma_1 \cdot (\sin\gamma_1 + \mu_L \cdot \cos\gamma_1)$ **(16)**

Total lift at waist: $F_Z = F_Z^B + F_Z^L$ **(17)**

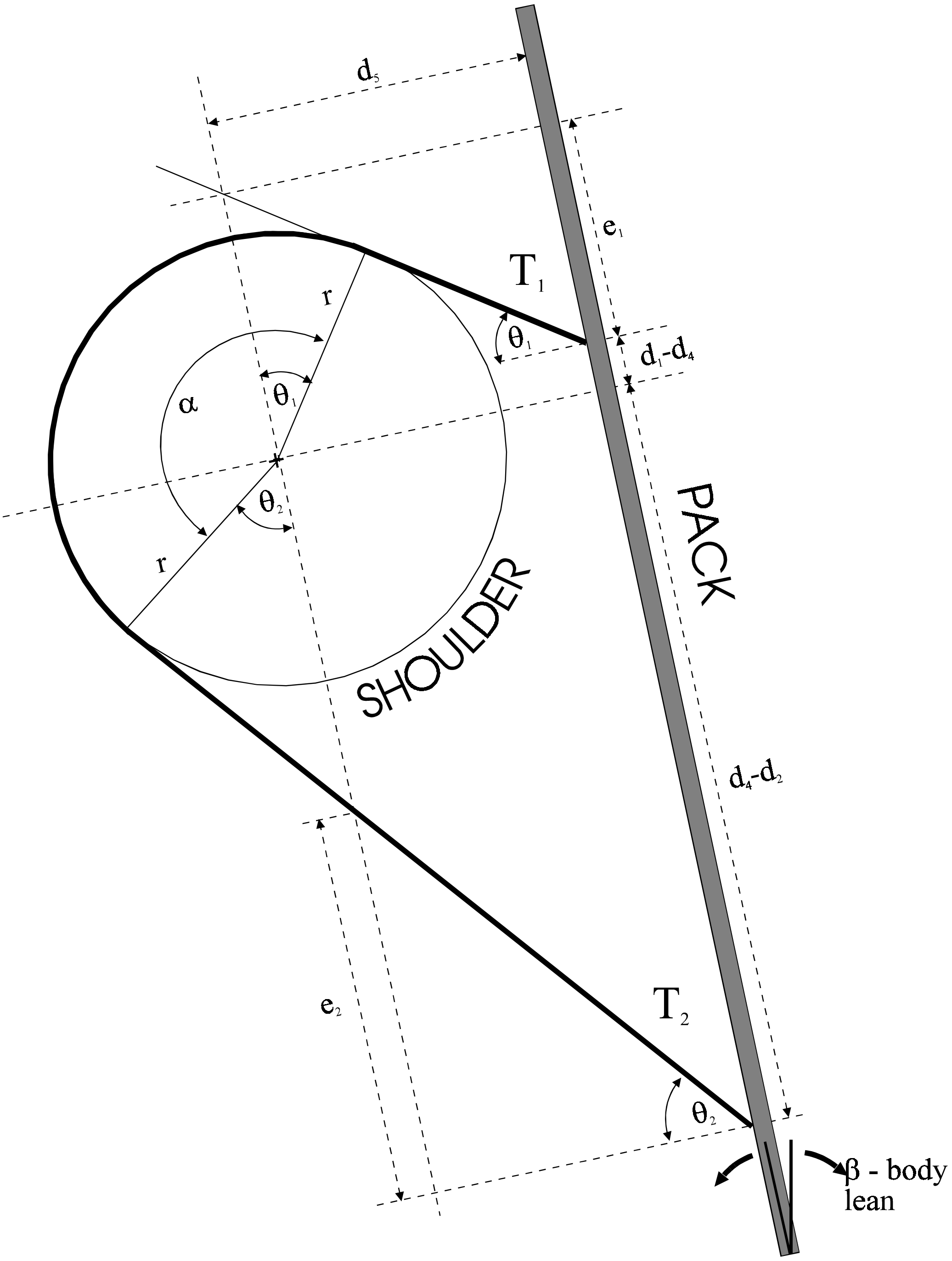

Figure 2. Shoulder wrap angle relations

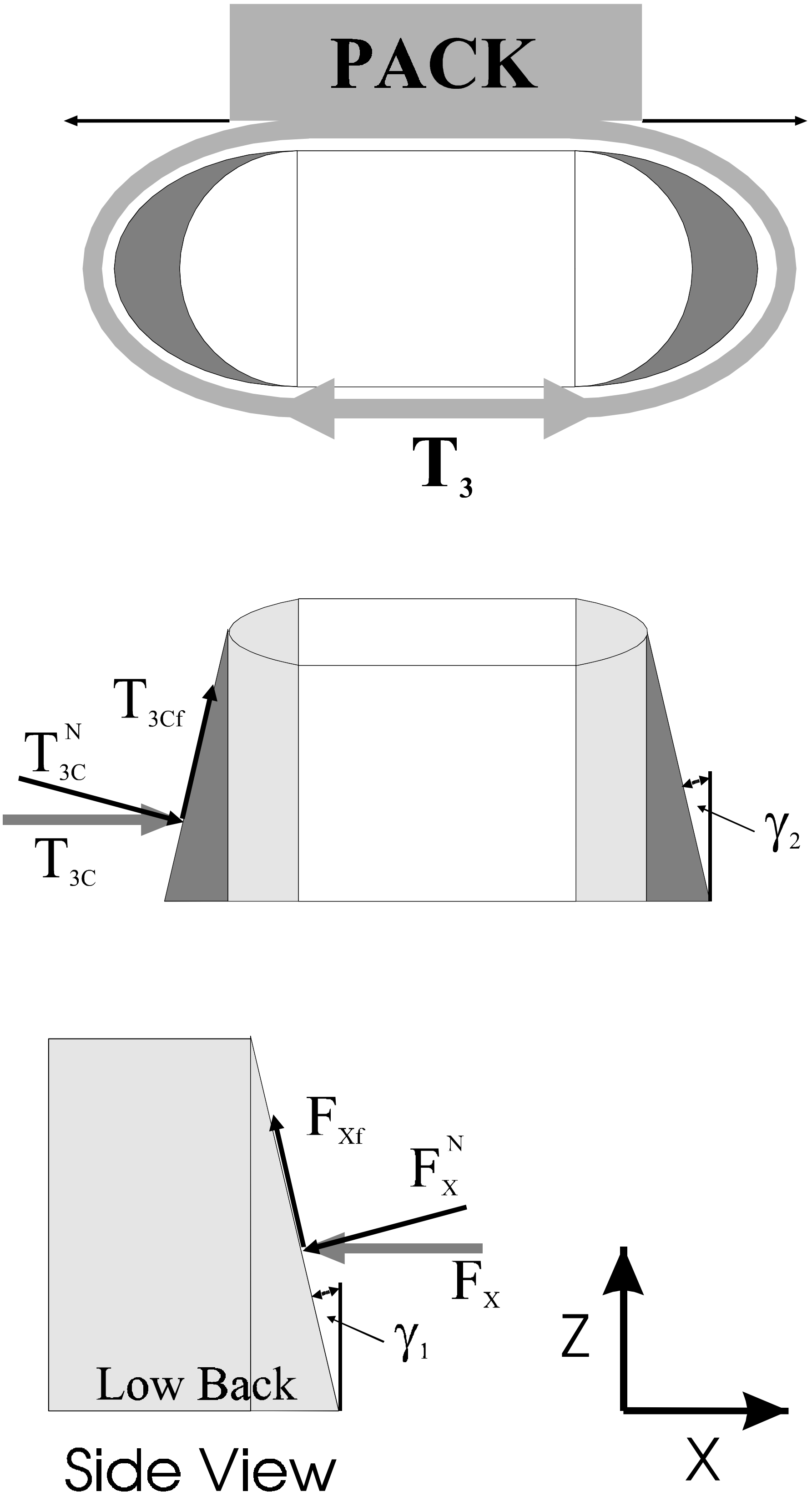

Figure 3. Waistbelt and lumbar pad models

The pack static equilibrium equations for force in the X direction, force in the Z direction, and moments about the centre of gravity can be simplified to the forms given in equations (2) through (5). These expressions can be solved for all of the unknown forces illustrated in Figure 1. However, another quantity of interest is the resultant normal force on each shoulder, S^N (see equations 11 to 13). Finally, the forces at the waist include contributions from the lumbar pad and waistbelt (Rigby, 1997) as shown in Figure 3 and equations 14 to 17. The key assumption is that the lumbar pad provides the maximum possible lift, with the waistbelt contributing the remaining support in the Z direction, if required to maintain static equilibrium of the pack.

The validity of these equations was examined by measuring the forces on several different pack designs mounted on instrumented manikins (Rigby, 1997). Given the respective input parameters for each pack, using the model to predict the unknown forces was quite good in almost all cases, falling within 10% of measured values. The exceptions only occurred in a couple of instances, where the forces were relatively low, and although the absolute error was small, the relative error exceeded this 10% threshold. This relatively simple rigid, two-dimensional model provides valid outputs for the packs and parameters tested.

Optimization of biomechanical model

The first issue is to determine the decision variables, or those variables that may be altered by the designer. To put this in context, there are three categories of values involved in the modelling process:

- *parameters*: externally determined values, which are input to the program, and not changed during the optimization;
- *decision variables*: values which can be changed during the optimization process to best achieve the specified objective;
- *state variables*: values that are calculated explicitly as functions of the parameters, decision variables and/or other state variables.

There is some latitude in selecting decision variables, depending on the purpose of the modelling run. As an initial scenario, assume that only the "heights" of the suspension systems attachment points can be varied (i.e. d_1, d_2, and d_3).

The next step is to formulate the objective function. Various definitions can address the ultimate goal of improving comfort for the bearer. Since there is no unique characterization of the most comfortable load distribution, various alternatives can be considered, with a typical version presented below. Minimizing the normal force on the shoulder, S^N, is used as a surrogate for shoulder comfort. The transverse force on the lower spine has been significantly correlated with pain and discomfort (Stevenson et al., 1996), which can be mitigated by reducing F_X. Finally, excessive vertical forces at the waist should be avoided as a general rule by lowering F_Z. To achieve this, one objective involves minimizing the weighted sum of these three forces, leaving it to the analyst's discretion to set the relative weights. This objective function is presented in the formulation below.

The relationships established by the biomechanical model described in the preceding section act as constraints on the design process. That is, any variable that is altered may affect many other quantities, so that these equations limit the feasible ranges for parameter changes. These relevant constraints are listed in the formulation below.

To complete the model, certain other bounds must be applied to ensure a reasonable result. Note that the biomechanical model formulation incorporates several implicit assumptions, some of which can be relaxed as model analyses progress. First of all, the moment equation was derived on the basis that the upper shoulder strap is attached above the centre of gravity, while the lower shoulder strap and the waistbelt lie below the C of G. Consequently, these dimensions (d_1, d_2 and d_3) are restricted accordingly in the constraints in the formulation below, although future models can easily circumvent this issue. In any case, the upper shoulder strap must be attached no lower than the lower strap (i.e. $d_1 \geq d_2$). In practice, a finite buffer could be required between them. The lower shoulder strap may be affixed below the centre of the lumbar pad (i.e. effective force application point in Figure 1), but not below the bottom of the rucksack. Similarly, the upper shoulder strap attachment is limited by the height of the pack. Finally, modelling the shoulder as a pulley with friction assumed that the tension is higher in the upper part of the strap (i.e. $T_1 \geq T_2$). There is no explicit control over this in the model, as this assumption guarantees a solution with T_1 larger (if a solution exists). Computer runs may also be conducted where the converse assumption is made, to see if the former case is always valid.

Finally, threshold limits for certain values may be recommended. Previous studies suggest an upper bound of 135 Newtons should be placed on F_X to remain within the comfort zone (Stevenson et al., 1996). Similarly, S^N may be constrained to lie below 280 Newtons. Rules of thumb over many years of experience have also implied that the support for heavy loads be split such that the waist bear about twice the amount of weight than do the shoulders (Pelot, 1995). This guideline does not account for the angle of the resulting normal force on the shoulders, so as a first approximation it is applied simply to the ratio of S^N over F_Z. The degree to which this condition is satisfied can be controlled by requiring the ratio to lie within a prescribed range centered on (2/3) as shown in the constraints below. Continuous improvements in pack suspension system designs may render this prerequisite obsolete.

Optimization formulation

Objective function: minimize $C_1 \cdot S^N + C_2 \cdot F_X + C_3 \cdot F_Z$

where: $C_1, C_2, \text{and}\, C_3$ are user-specified coefficients

Subject to these constraints:

Equations 1, 2, 3, 5, 6, 7, 8, 9, 10, 15, 16 and 17 (from above)

Additional constraints:

$$S^N \leq 280 \qquad F_X \leq 135 \qquad d_1 - d_2 \geq 0 \qquad d_1 + d_3 \leq h_Z$$

$$d_2 \geq -d_3 \qquad d_3 \leq V_Z \qquad d_1 + d_3 \geq V_Z \qquad d_2 + d_3 \leq V_Z$$

$$\left| \frac{S_N}{F_Z} - \frac{2}{3} \right| \leq 0.1$$

Base Case analysis

Representative data from a typical commercial pack are presented in Table 2. Aside from pack dimensions, anthropometric data and friction coefficients were established during laboratory experiments (Rigby, 1997). The mass of 30 kg (66 lbs) represents a reasonable load for a typical military mission, although computer runs can be conducted to evaluate the effects of much heavier weights sometimes borne by the soldier. By default, the C of G is assumed to be at the volumetric centre of the pack. Original data is input in specified units, then converted for use in the model. The decision variables are set to the current pack dimensions initially.

Giving equal weight of 1.0 to each force coefficient C_1, C_2 and C_3 when minimizing the objective function yields the results shown in Table 3 for several variations on the Base Case. The optimization procedure does not find a feasible solution for the Base Case itself. In other words, for the given parameters, there is no choice of the three decision variables that satisfy all of the constraints. Further analysis indicates that the restriction being violated is the upper bound on the transverse force at the lumbar level. With the given configuration, it is not possible to keep F_X below 135 Newtons. Removing this constraint, and running the model again results in a feasible solution, listed as Run 2 in Table 3. The minimum F_X attained is 155.3 N.

To achieve this, the shoulder straps are attached to the pack as high as allowed (recall that the lower strap cannot rise above the Centre of Gravity), and the waistbelt as low as possible. Note that $d_3 = 0$ does not mean that the waistbelt is lowered relative to the body, since the waistbelt-to-shoulder distance d_4 is constant, but rather that the bag is raised so that the bottom is flush with the centre of the lumbar pad. The minimum objective value results from the sum of its three force constituents. Thus the model lowers S^N, F_X and F_Z as much as possible. The ratio of shoulder to waistbelt lift is within its prescribed tolerance of (2/3)± 0.1, which means that this constraint is redundant for the conditions of this run. The ratio falls naturally near the desired value. It is clear that the attachment locations of the upper strap and waistbelt in this scenario are too close to the pack edges to be practical, but the purpose of these evaluations is to understand the fundamental design trade-offs. In a more realistic analysis, allowable ranges on the attachment region for each strap can be included in the model.

Table 2. Base Case Data

Biomechanical Load Carriage Model : Base Case					
	ORIGINAL			**CONVERTED**	
Description	**Data**	**Units**	**Notation**	**Data**	**Units**
mass of pack + load	30.000	kg	W	294.3	Newtons
depth of pack	34.000	cm	h_X	0.3400	m
height of pack	42.000	cm	h_Z	0.4200	m
CofG from back	17.000	cm	v_X	0.1700	m
CofG from bottom	21.000	cm	v_Z	0.2100	m
shoulder strap top position from WB	43.333	cm	d_1	0.4333	m
shoulder strap bottom position from WB	2.000	cm	d_2	0.0200	m
waistbelt position from pack bottom	6.667	cm	d_3	0.0667	m
waistbelt to shoulder centre	43.000	cm	d_4	0.4300	m
pack back to shoulder centre	14.300	cm	d_5	0.1430	m
shoulder radius	7.000	cm	r	0.0700	m
body lean angle	10.000	deg	ß	0.1745	rads
low back angle	7.000	deg	γ_1	0.1222	rads
hips angle	10.000	deg	γ_2	0.1745	rads
shoulder friction coefficient	0.35	---	μ_S	0.35	---
low back friction coefficient	0.35	---	μ_L	0.35	---
waistbelt friction coefficient	0.35	---	μ_B	0.35	---

Table 3. Optimization results for Base Case (BC) and some variations

Run	**Conditions**	**d_1 (cm)**	**d_2 (cm)**	**d_3 (cm)**	**v_X (cm)**	**v_Z (cm)**	**S^N (N)**	**F_X (N)**	**F_Z (N)**	**Obj (N)**	**S^N/F_Z**
1	Base Case (BC)	infeasible									
2	BC (no limit on F_X)	42.0	21.0	0.0	17	21	127.8	155.3	215.8	498.9	0.592
3	BC with CofG free	32.2	-4.8	4.8	10	37	109.6	103.6	193.5	406.7	0.566
4	BC with CofG free & no limit on S^N/F_Z	38.5	37.0	0.0	10	37	32.7	77.5	270.6	380.8	0.121

It is interesting to examine the impact of allowing the Centre of Gravity to move. Reasonable bounds are imposed by restricting the distance of the C of G from the back to vary between $10 \leq V_X \leq 30$ cm., and the position from the bottom of the bag to lie between $10 \leq V_Z \leq 37$ cm. The output is shown as Run 3 in Table 3. To minimize the forces, the load C of G falls as close to the back and as high as possible. This is consistent with empirical observations in field studies (Hinrichs et al, 1982). The objective value is lower than in the previous run, since allowing the C of G to move corresponds to more degrees of freedom. Notably, each of the three target forces has a reduced magnitude. The lower shoulder strap is attached below the waistbelt, hence the negative distance. The fact that d_2 is equal in value and opposite in sign to d_3 indicates that the shoulder strap is secured right at the bottom of the pack. Both the lumbar transverse force and the shoulder normal force are within the recommended threshold values. The shoulder/waist split constraint is binding at the optimum, which means that the 2:1 ratio is approximately maintained only because of the explicit condition included in the formulation.

Relaxing this last requirement results in the output labeled Run 4 in Table 3. The suspension system attachment points have changed, dramatically in the case of the lower shoulder strap. The effect of raising the shoulder strap attachment points is to remove much of the vertical load from the shoulder, which is then transferred to the hips, resulting in a higher F_Z, and a markedly reduced shoulder-to-waist force split. The transverse lumbar force is significantly reduced and the overall objective function is much lower. Thus artificially promoting a "desirable" shoulder-to-waist load ratio may result in significantly higher forces being exerted on the bearer.

Summary

These optimization results provide an overview of the types of issues that may be explored through this biomechanical model. A particular pack may be represented using the appropriate parameters, and the model can predict the changes associated with specific design changes. Alternatively, monographs may be produced showing the optimal solution for a wide range of combinations of the decision variables. Such a comprehensive set of tests would provide as complete a picture as possible of the interactions inherent in the biomechanical model, which ultimately can enhance the design process. Different objective functions can be introduced, since there is no single answer to the question of what is the “best” combination of forces for the bearer. Finally, the model can be used to perform sensitivity analyses on one or more input parameters.

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Identifying and Modelling the Dynamic Behaviour of Load Carriage Systems

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Summary

This paper describes a UK MOD funded research project that aims to identify mathematical models for the dynamic behaviour of backpack suspensions. A test-rig is described which can be used to collect the dynamic data required, and the processing of the data is briefly discussed. The resulting pack suspension models can be combined with a human locomotion model, and used to study the effects of design changes that alter pack dynamics.

Introduction

Current backpack designs have evolved through a process of trial and error. In other words, new designs have been based on previous experience and the designer's judgement, rather than being based on theoretical analysis. Each design iteration has been tested using human trials and, as a result, design evolution has been slow and costly.

In engineering design, theoretical analysis and computer modelling have long been used to obtain better designs with a minimum of physical prototyping. Most of the design iterations for an engineering product are undertaken using virtual prototypes (computer models). Although the advantages of such an approach are clear, it is difficult to apply to backpack design because textile products are inherently less predictable and more difficult to analyse theoretically than normal engineering products. To compound the problem, there is considerable variation amongst the soldiers that use the pack, and in the contents of the pack.

Despite these difficulties, there has been research activity in this area. For example, theoretical analysis has been applied to load distribution within the pack and the calculation of the corresponding mass properties [1]. Static biomechanical models have also been developed to calculate the unknown strap and interface forces given that there are sufficient measured forces and geometric parameters to make the problem statically determinate [2]. This paper describes a research project being undertaken for the UK MoD, the aim of which is to identify mathematical models for the dynamic behaviour of backpack suspensions. These models will be used to predict the effects of design changes, which alter the suspension characteristics.

A test-rig has been developed to identify dynamic suspension models for existing packs. The test-rig has similarities with the load carriage simulator at Queens University in Kingston, Canada [3]. The Queens facility has been developed to provide a means of testing pack designs prior to human trials, and relies on empirical correlation's between test-rig measurements and human trial data. Conversely, the authors' test-rig has been designed to collect the dynamic data required to identify mathematical pack suspension models.

Modelling pack dynamics and human locomotion

As explained above, the aim of the authors' work is to develop computer models that allow the pack designer to study the effects of different pack dynamics on locomotion performance. In this context, the general modelling concept is as follows.

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Sub-Models:
pack suspension model
human locomotion model

Model Inputs:
gait data
anthropometric data
mass properties

Model Outputs:
pack forces exerted on body
relative motion between pack and body
soldier's joint loads
soldier's energy consumption

Initially, the authors are studying vertical pack dynamics only, which are the most important for regular marching. If the results of this work are successful, then a full 3-D study will be considered. The requirements of a vertical model can be understood by considering the schematic shown in Figure 1. The pack and torso are represented by masses m_P and m_T respectively, and are connected by the pack suspension model. The latter will be some non-linear function of the relative motion between pack and torso (z and $\dot{z}$) that returns the net vertical force between pack and torso (F_{PAC}). The locomotion model is a function of the gait data and the force required to support the torso (F_{LEGS}). If the soldier's joint loads are required, then the locomotion model would have to be anthropomorphic. If all that is needed is an estimate of energy consumption, then a black-box model would suffice.

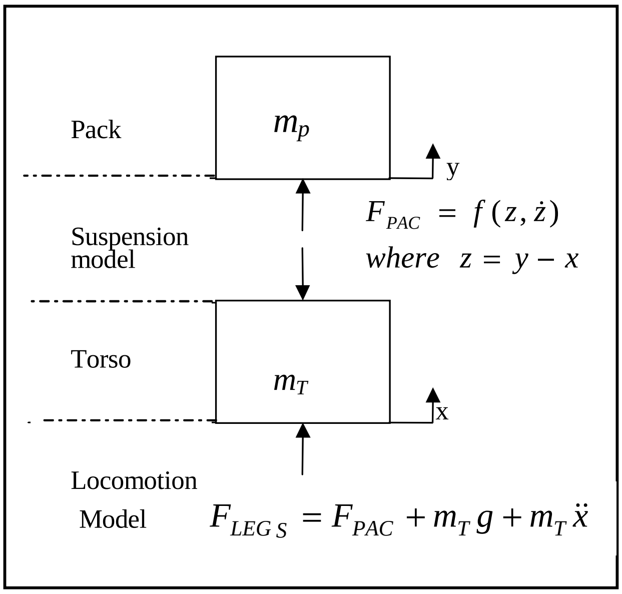

Figure 1. Model Schematic for Vertical Pack Dynamics

The main subject of this paper is the identification of the F_{PAC} function for existing packs. This requires the measurement of F_{PAC}, z and $\dot{z}$, under varying experimental conditions and for different packs, and also the identification of the corresponding mathematical pack suspension models.

Test-rig design

To identify the F_{PAC} function for an existing pack, it is necessary to measure F_{LEG}, z and $\dot{z}$ under varying experimental conditions. The test-rig developed for this purpose consists of a mannequin mounted on a hydraulic ram and equipped with appropriate instrumentation (Figures 2 & 3).

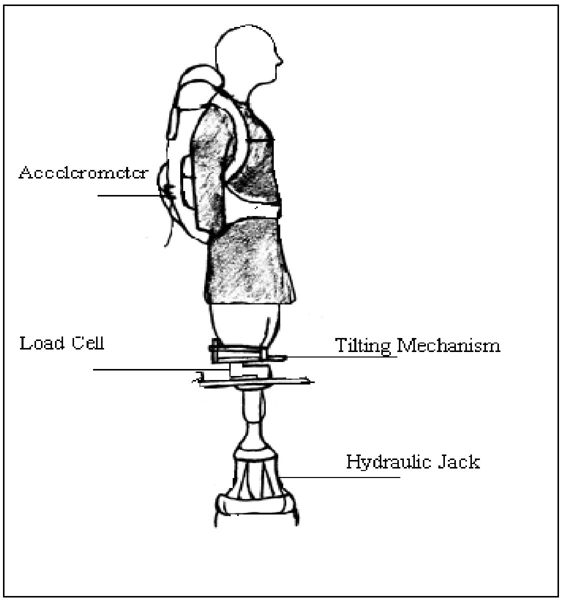

Figure 2. Schematic of Load Carriage Rig

Figure 3. Photo of Load Carriage Rig

The mannequin is built on a steel frame using three times the amount of fibreglass found in a display mannequin. This reinforced construction has been used to withstand the expected dynamic loads. The steel frame allows for direct attachment to a mounting plate. The mannequin is covered in an orthotic-prosthetic material (Bocklite), to mimic human tissue.

The mannequin is mounted on a tilting assembly which allows it to adopt an angle of forward lean appropriate to the load being carried. This assembly sits on top of a load cell which measures the vertical load supporting the mannequin, (F_{LEGS}). The entire arrangement is mounted on the hydraulic ram which provides the required cyclic vertical motion.

The vertical motion of the mannequin is measured by a displacement transducer that is an integral part of the hydraulic ram. The vertical motion of the pack is measured by an accelerometer attached to the rucksack.

Test-data processing

With the mannequin being moved sinusoidally, the instrumentation allows the capture of the load supporting the mannequin (F_{LEGS}), the displacement of the mannequin (x), and the acceleration of the pack ($\ddot{y}$). The latter is integrated to give the displacement of the pack (y), and thus the relative displacement ($z = y - x$). Knowing the masses and accelerations of the pack and mannequin, the pack force can be obtained from Newton's II law as follows:

$$F_{PAC} = F_{LEGS} - m_T g - m_T \ddot{x} = m_P \ddot{y} + m_P g$$

Note that this gives two independent measures of F_{PAC}.

This quasi-sinusoidal data is then processed to obtain the amplitudes of z and F_{PAC}, and the phase difference between them. This is repeated over a range of frequencies and amplitudes, providing a database of frequency response data. By considering only their fundamental components, we can say

$$z = \hat{Z}\sin(\omega t)$$

and $$F_{PAC} = \hat{F}_{PAC}\sin(\omega t + \phi)$$

By curve fitting the frequency response data, relationships for the amplitude ($\hat{F}_{PAC}$) and phase (ϕ) of the pack force can be obtained, which have the following general form:

$$\hat{F}_{PAC} = fn(\omega, \hat{Z})$$
$$\phi = fn(\omega, \hat{Z})$$

Finally, these frequency domain relationships can be used to establish the required time domain function for pack force, $F_{PAC} = fn(z, \dot{z})$. This is the pack suspension model that can be used, along with a human locomotion model, to assess the effects of altering pack dynamics.

Conclusions

A test-rig has been designed to measure the dynamic behaviour of backpacks and thereby identify mathematical pack suspension models. Such models can then be used, along with a human locomotion model, to predict the effects of design changes which alter the suspension characteristics. The long-term aim of this work, and other modelling work like it, is to reduce the reliance on human trials in the design evolution of future backpacks. The return would be better designs, produced more quickly and at lower cost.

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14. Abstract

On 27-29 June 2000, NATO, Partners for Peace and Non-NATO nationals from 10 countries met in Kingston, Canada to discuss soldier mobility through innovations in load carriage system design and evaluation. Sponsored by the Human Factors and Medicine Panel (HFM) of the North Atlantic Treaty Organization's Research and Technology Organization, the specialist's meeting participants examined the current state of knowledge in load carriage, exchanged findings from recent research and development initiatives, explored what initiatives were needed to develop new concepts in design and evaluation and identified opportunities for collaboration. Specific sessions were held on the physiology, biomechanics and performance measures of load carriage, approaches and tools for assessment, development and validation of objective tests and their use in design solutions, mathematical modelling and the accuracy of pressure sensor measurement systems. There were two keynote addresses, twenty-five scientific papers, four workshops on future directions and tours of load carriage research facilities during the conference. The meeting unveiled many new findings, such as: possible energy transfers between body segments and between the pack and the person; objective assessment technologies for better understanding and design of load carriage systems; an interest in mathematically modelling the pack-person interactions and their effects on the carrier; and a willingness to work together toward sharing resources, data and the development of an improved STANAG for personal load carriage.

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