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Development and assessment of the Canadian personal load carriage system using objective biomechanical measures

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The Defence Research and Development Canada—Toronto managed a collaborative team of designers, biomechanists, ergonomists and military stakeholders in the development of a new personal load carriage (LC) system for the Canadian Forces. Ergonomics design principles using objective measurement tools and user-centred feedback from soldiers were considered essential to system development. The purpose of this study was to provide a detailed report of contributions by biomechanical testing to the final design of the final Canadian LC system. The Load Carriage Simulator and Compliance Tester were used to test design iterations of: three fragmentation vests, seven tactical vests and three iterations of the backpack. Test data were compared to a data pool of seventeen previously tested systems. Results indicated that the objective measures helped the design team by: (1) quantifying and understanding the consequences of various design changes; (2) predicting soldiers' responses to design changes in skin contact pressure, force and relative motion; (3) objectively comparing design iterations to other systems; and (4) providing information quickly so that ideas and recommendations 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.

1. Introduction

Defence Research and Development Canada (DRDC)—Toronto undertook a research and development programme 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 also, by better protection within the load carriage system to improve soldier safety in future conflict or peacekeeping operations. The Canadian soldier modernization programme involved two components: upgrading the current soldier system under

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Crown acquisition project L2646, Clothe The Soldier (CTS), and developing future soldier systems under Crown project D6378, Integrative Protective Clothing and Equipment (IPCE).

A comparison of the 1982 Canadian military backpack with current state-of-the-art civilian packs indicates the need for both upgrading and modernization of the soldier load carriage system. Over the years, civilian backpacks have incorporated several new design features that contributed to improved function, comfort and quality. Although these additions have become the commercial standard, the procurement procedure for military acquisitions means that one common pattern is adopted and acquired for all subjects. This pattern remains frozen until the next generation of acquisitions occur.

The current 1982 Canadian issue for ballistic protection is a fragmentation vest (called Gen II-97F by Pacific Body Armour). It has back and front body panels that are lined with Kevlar® and held together with Velco®. It also has a Kevlar® filled detachable collar. For fighting and battle orders, a webbing system is used where a shoulder harness supports a waist belt onto which almost all of the ammunition, protective equipment and sustainability rations are held. For marching and heavy load carriage needs, an external frame suspension system is issued. It consists of lightly padded shoulder straps and waist belt that attach to a metal and wire mesh frame onto which a rucksack is mounted at the top and an overnight valise and sleeping bag are mounted on the bottom. There were numerous complaints about system components, particularly the rucksack, but also about the lack of integration of the load carriage components.

A review of backpack and load carriage system literature reveals that there are few scientific articles that assess pack design. However, there are numerous articles, especially in magazines like *Backpacker,* which give advice about the types of features needed for specific functions. These articles are either reviews or pack evaluations by manufacturers or expert trekkers. Franks (1991), Getchell (1991) and Jenkins (1992) described the purposes of an internal and external frame pack that have implications for military use. They describe the external frame as having an advantage for carrying heavy loads and awkward loads and providing better ventilation, but point out that they have mobility and balance problems due to a high centre of gravity. Internal frame packs have advantages for better control and stability because they are closer to the body and two stays in suspension system's mould to create a custom fit. However, they have poorer back ventilation and often have poorer load carrying capacity. Getchell and Howe (1994) felt that internal frames allowed more flexibility in terms of types of frame sheet advances for additional support.

Concerning evaluation, Parker (1990) and Howe (1994) reported systematic scientific approaches using expert trekkers who trialled as many as eight different packs over several days and were able to rate their performance and special features. It would appear that in the past, these subjective evaluations had been more effective at determining preferred design features than either physiological or biomechanical measures. For example Kirk and Schneider (1992), using both physiological and subjective responses, could not differentiate between two packs under similar load conditions. Using biomechanical gait measures, Martin and Nelson (1982) did not see differences between pack types or load configurations. These unimpressive scientific results for evaluation of pack designs led the Queen's University Ergonomics Research Group to consider development of an objective measurement system for evaluation and assessment of pack design. The standardized biomechanical measurement tools described in a companion paper provide some details about the effectiveness of this approach (Stevenson *et al.* 2004).

The task assigned to Queen's University was to use these biomechanical measurement tools to assist with the development of a new Canadian CTS load carriage system. The university research group became part of a comprehensive team, led by DRDC Toronto, that included designers/manufacturers (Pacific Safety Products and Ostrom Outdoors Inc.), human factors assessment specialists (Human Systems Inc.), and the necessary military portfolios needed to develop a new modernized CTS load carriage system. Prototype design iterations were evaluated through either (or both) of the biomechanical standardized assessments at Queen's University, and/or by soldiers from a number of military bases who participated in focus groups and field trials (figure 1). The designers were asked to respond to the design changes recommended by either the biomechanical analyses or soldiers' feedback in their next design iteration. An ergonomics approach was adopted whereby design decisions were made from the soldier outward so that the decisions were made in the order of fragmentation vest, load carriage vest and finally the backpack (also called rucksack). The design team was judged to be well-managed

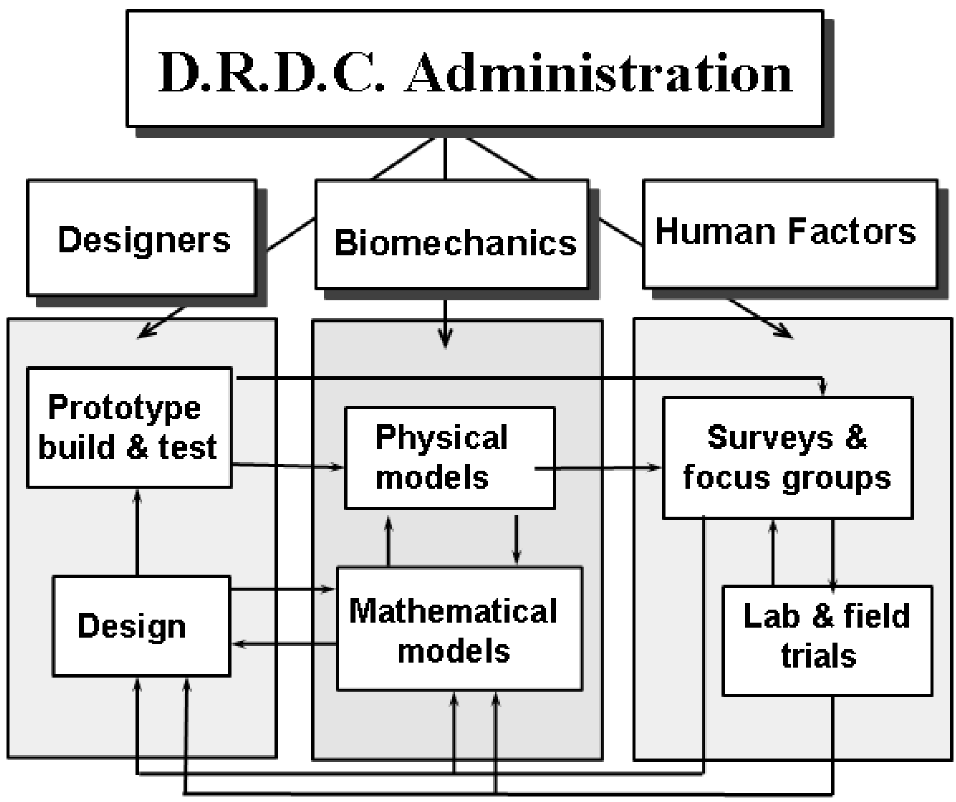

Figure 1. Model of interactions and responsibilities of DRDC Toronto's CTS load carriage system design team.

and effective both in terms of time, costs and incorporation of the end users in the design process.

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 specific purposes of the study were to use the standardized biomechanical simulations to evaluate: (1) three fragmentation vests; (2) seven webbing or load carriage vests under two conditions, with and without a fragmentation vest; and, (3) three design iterations of the CTS rucksack in comparison to a database of pack designs. Feedback on these design iterations was either part of making a decision between various design styles or an evaluation of a design prototype. Using these tools, design recommendations were provided to the design team at their regular meetings for input into the next prototype.

2. Methods

The testing programme for each sub-study was selected to provide the most appropriate feedback relating to conditions of use. Two assessment tools and their individual test protocols will be described briefly.

2.1. *Load carriage simulator*

The Load Carriage Simulator, described in more detail in the companion paper, was designed to capture 3D dynamic responses of a LC system on the human torso during normal gait motions. The LC Simulator outcome measures were validated both by other objective measures and by soldiers' subjective responses to a number of LC systems (Stevenson *et al*. 1997a, Bryant *et al*. 2001). The computer-controlled pneumatic system was programmable for walking, jogging or running using sinusoidal patterns that reflect 3D human gait patterns (Inman *et al*. 1994). A 50th percentile anthropometrically adjusted male mannequin, covered with a skin analogue called Bocklite®, was used as the standardized soldier for all tests. Outputs were taken from three measurement systems. A six degree of freedom AMTI 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 placed over the shoulders, upper and lower back, and waist area in order to measure mean pressures, peak pressures and mean contact forces in each area. These were calibrated to an accuracy of 4 kPa using specialized protocols (Bryant *et al*. 1996, Morin *et al*. 2001). Relative displacement of payload items in the LC system was measured using up to four Polhemus Fastrak® magnetic sensors. When validated against Optotrak®, it had a dynamic accuracy of 0.65 mm (Bryant *et al*. 1996). For fighting order assessments, the Fastrak® sensors were placed on specific kit items and for marching order assessments, one sensor was placed in the pack. The motions of the payload and kit items were described relative to the LC Simulator mannequin during gait.

The protocol for LC Simulator testing involved: (a) carefully dressing the mannequin with the test gear for fighting order assessments, (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 (in order to simulate a balanced load), and (d) collecting five repetitions of 10 s of data every 5 min at a data acquisition rate of 50 Hz. The speed of LC Simulator motions was standardized at 3.0 Hz (9.3 km/hr) for jogging simulations and at 1.8 Hz (5.6 km/hr) for walking simulations. Post-processing of raw data was conducted on all outcome measures. For the fragmentation vest study and the load carriage vest study, results were compared to other prototypes and for rucksack iterations study, data were compared to a previously collected database of other packs tested under the same conditions.

2.2. *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. It 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) $\pm$ 18° of lateral bending and (c) $\pm$ 12° of torsion. 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 (Bryant *et al.* 1996).

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 axis of motion.

3. Part I: Assessment of fragmentation vests

3.1. *Introduction*

The purpose of this study was to examine three designs for the fragmentation (Frag) vest (FV) both objectively and subjectively. The Frag vests under review were: the current Canadian vest (FV-1) and two new prototypes, FV-2 and FV-3. The main differences in features between vests were: the FV-1 had overlap junctions of front and back panels at the shoulders and a removable neck guard, the FV-2 had side junctions and a lower profile removable collar and the FV-3 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.

3.2. *Methodology*

To examine the dynamic responses of the three Frag vests and their impact on the user, the LC Simulator was used. The mannequin was programmed for 3.0 Hz (9.3 km/hr), equivalent to jogging. Data were obtained 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 information on user discomfort and other factors related to mobility, test subjects completed a circuit of shuttle run, leopard crawl, agility obstacles and range of motion tests, and submitted individual Likert Scale responses as well as focus group feedback.

3.3. *Results and discussion*

Table 1 provides a summary of the rank order results for the three Frag vests. There were negligible differences between them for relative kit motion, hip moments and shear forces, but the pressure system indicated some high pressure points. The FV-1 vest had local pressures of 70 kPa in the collar area because of seams and edges and the FV-2 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 14 kPa can cause complete cessation of blood flow to an area (Holloway *et al.* 1976), and 90% of soldiers reported discomfort with over 20 kPa of mean pressure for a 6 km march (Stevenson *et al.* 1997b), it was concluded that these point pressures would cause complaints and possibly injury to the skin. For peak pressures, 35 kPa was the level where soldiers began identifying discomfort. Only the FV-2 vest did not exceed that recommended limit for peak pressure (Reid *et al.* 2001a). In the human trials, subjects reported interference between specific kit items and the Frag vests. There were occasional reports that ballistic layers and edges were poorly positioned for comfort. In addition, the shoulder closures on the FV-1 and FV-3 vests were considered to be uncomfortable.

3.4. *Conclusion*

In conclusion, the FV-2 fragmentation vest was recommended to the CTS design team with specific improvements. Research feedback on this phase was provided to DRDC Toronto within two weeks of receiving the equipment.

4. Part II: Assessment of tactical vests

4.1. *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 results needed to be provided to the design team quickly in order to uncover potential problems or compatibility issues

Table 1. Summary of rank order results for three fragmentation vests

Variables	FV-1	FV-2	FV-3	Discussion
LC simulator measures				
– Displacement (mm)	2	1	3	Negligible motion for all Frag vests
– Peak Pressure (kPa)	2	1	3	Collar (FV-1), shoulder closure (FV-3)
– Forces & Moments	1	2	2	Negligible effects for all Frag vests
LC compliance measures				
– Forward (Nm/deg)	1	2	2	FV-2 & FV-3 extend down torso
– Lateral (Nm/deg)	2	1	3	Side closures reduce stiffness
– Torsion (Nm/deg)	3	1	2	FV-2 had larger gap at waist with fastener
Human factors				
– Subjective reviews	3	1	2	Shoulder closures were uncomfortable One buckle on TV created a pressure point

and make design recommendations. The design team did not wish to conduct human trials on this many iterations, so biomechanical testing was the only method used to compare the seven LC systems.

4.2. *Methodology*

In this study, the LC Simulator was used under jogging conditions comparable to 3 Hz (9.6 km/hr). 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 FV-1 Frag Vest had a mass of 2.72 kg. The four Fastrak® motion sensors were placed within non-metallic casements in the C-9 magazine, the water canteen and two C-7 magazines. The outcome measures were: (a) total kit maximal motions in x,y,z and the vectoral sum r of the maximal motion; (b) maximal forces (normalized to total payload) and moments in x,y,z and r at the hip level from the AMTI load cell; and (c) peak pressure, mean pressure and contact area of the Tactical Vests from the Tekscan® pressure measurement system. In addition, each configuration was checked for compatibility in terms of geometry, conflict with the shoulder strap or waist belt and other conflicts. Compatibility was further assessed 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. In addition, the seven systems were identified by rank order from first to last on each outcome variable (Bryant *et al*. 1997a).

4.3. *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. Since there were no significant differences between total kit displacements, peak pressures and mean pressures due to wearing the fragmentation vest, it would not matter to soldier comfort whether a Frag Vest was worn for day-to-day duties. However, the added weight and heat load may affect soldier comfort or performance. This is a moot point in battle when personal safety (via evading or returning fire) is of paramount concern. However, during non-combat conditions, soldiers would have an increased physiological demand while wearing a fragmentation vest.

The objective variables evaluated for the LC Simulator were: net relative displacement and mean 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. Soldiers preferred a Tactical Vest where the payload was held tightly to the body, as

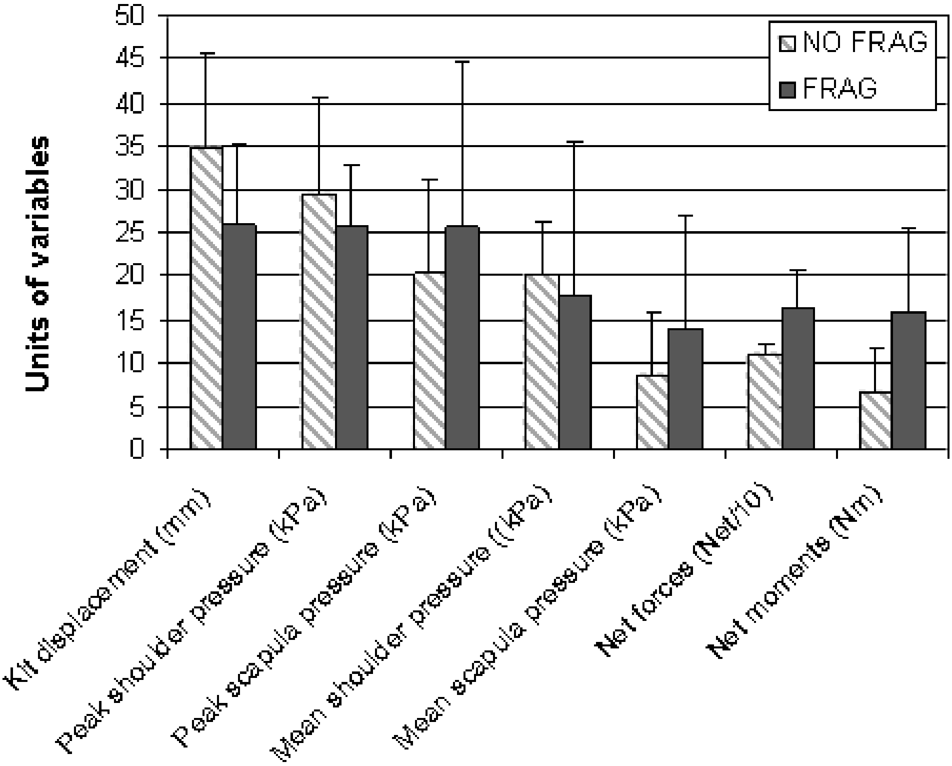

Figure 2. Effect of wearing a fragmentation vest on LC simulator measures. Net forces ($\div 10$) and moments were significantly different ($p > 0.019$) as a result of the added weight in the Frag vest condition.

it was carried more efficiently and proved to be less distracting (Tack and Gaughan 1996). The second best system was LV1. In this case the fragmentation vest served to reduce the relative motion between the kit and the mannequin. This occurred in most other cases as well.

Figure 4 shows the mean shoulder pressure when the anterior and scapular regions are combined. The top ranking systems were SV3 followed by Web2, a webbing-based system (Bryant *et al.* 1997a). Maintaining a low mean pressure is important since 90% of soldiers report discomfort at 20 kPa of pressure (Stevenson *et al.* 1997b). This means that only the SV3 was within recommended limits for both conditions. The importance of keeping the mean shoulder pressures at a minimum in fighting and battle orders (meaning sufficient clothing and supplies to sustain soldiers for 8 and 24 h respectively) is critical if it is considered that the rucksack will also add to the shoulder pressure experienced by soldiers in the marching orders (self-sustaining supplies for 72 h). 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. Results from human trials confirmed that there were similar hotspots to those identified on the LC Simulator. In subsequent trials, soldiers also reported that excessive looseness of kit items in LC Vests caused

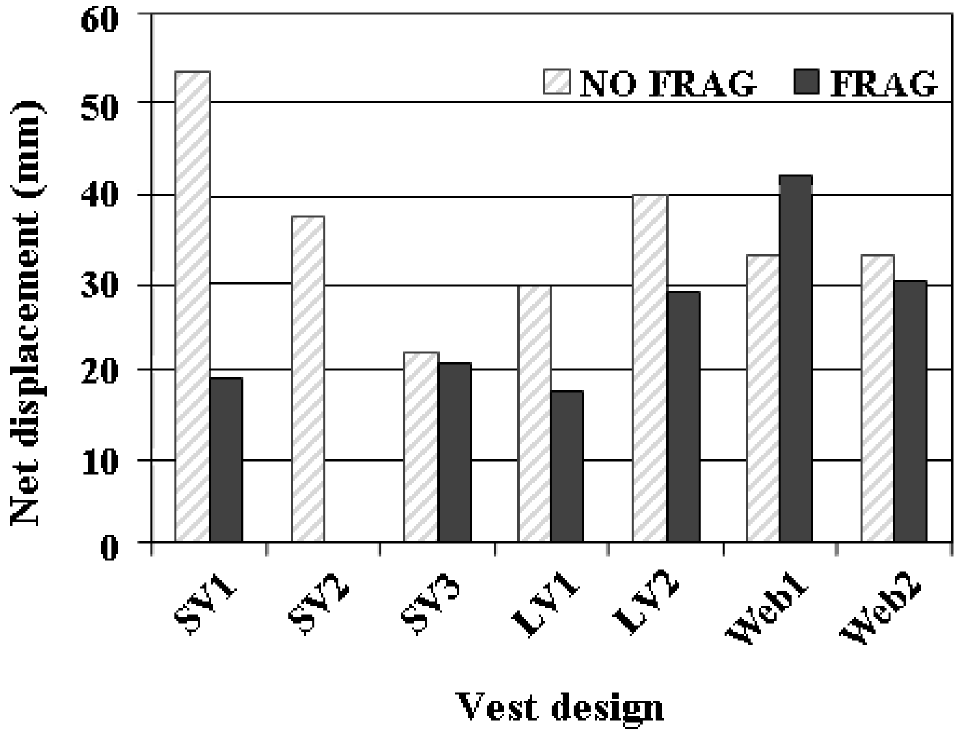

Figure 3. Effect of tactical vest designs on net relative kit displacement. SV3 and LV 1 were first and second in rank order.

difficulty in making certain movements during certain battle order tasks (Tack and Gaughan 1996).

4.4. *Conclusions*

In conclusion, based on LC simulator data and limited human factors data, the SV3 vest was recommended to the Canadian Forces under the following conditions: (1) SV3 be designed with protected spaces to receive the backpack on the shoulder straps, waist belt and back support area; (2) shoulder stitch locations and a padded shoulder design be implemented to reduce shoulder pressures; (3) conflict be removed between the SV3 vest and C-9 magazine; and (4) FV-1 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 to obtain feedback on final design features. After these trials, a modified SV3 was renamed and became the Tactical Assault Vest (TAV) for the final system. Only 3 weeks of objective testing were needed to give the DRDC Toronto and design team initial feedback on the study.

5. Part III: Evaluation of rucksack designs

5.1. *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.

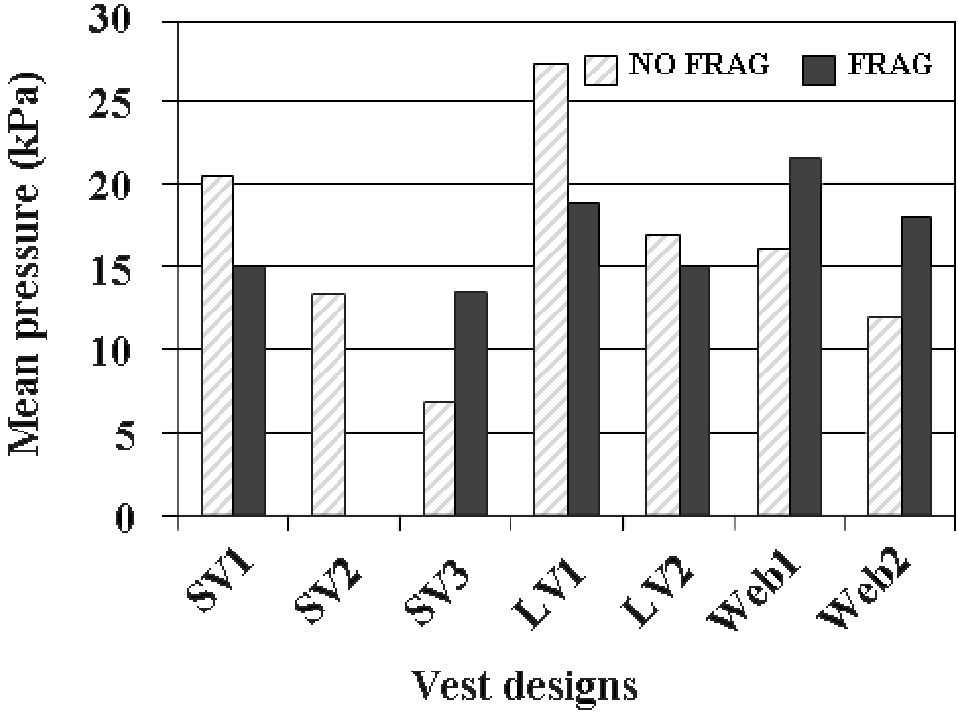

Figure 4. Effect of tactical vest designs on mean shoulder pressure. SV3 and Web 2 were first and second in rank order.

Prior to commencing this study, the Queen's Ergonomics Research Group had assessed 17 military and civilian LC systems backpacks on the LC simulator in order to create a database of comparable packs (Bryant *et al.* 1996). For all of the LC Simulator and LC Compliance variables, a normalized distribution was created so that the mean (50th percentile), upper decile (90th percentile) and lower decile (10th percentile) scores could be identified. These decile scores were used to assess prototypes of the CTS rucksack design. The purpose of this study was to assess three design iterations of the CTS rucksack with objective measures and to recommend solutions to design problems prior to development of the next iteration.

5.2. *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, 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 Assault Vest (TAV) were worn under packs during all tests.

Prior to testing, the mass properties of the system were taken, including: the mass of the pack plus payload, its centre of gravity and the physical dimensions. The systems were carefully adjusted to suit the mannequin size. The standardized strap conditions consisted 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 protocols, implemented for both the LC Simulator and LC

Compliance Tester, were followed (Stevenson *et al.* 2004). 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 database of previously tested packs.

5.3. *Results and discussion*

The masses of empty LC systems were 3.4 kg, 4.8 kg and 4.35 kg for the K, M and F systems respectively. These changeable masses were due to extra cloth and fasteners to make the various systems, especially for the modular system. The payload volume also changed because of pack designs, but this did not affect the results as a stable payload used for all tests. All variables, except those that are normalized (thus difficult to understand numerically) and individual pressure areas (better understood if summed across regions), will be described below.

Figure 5a shows the torsional stiffness of the suspension systems in Nm/deg as measured from the LC Compliance tester. This result meant that the pack frames' resistance to gait and mobility motions were above the mean around all three axes. The prototype backpacks were probably affected by the addition of the design feature of lateral rods in the suspension system (Reid *et al.* 2001a). The poorest performers in pack frame stiffness about all three axes were several other military systems and external frame packs. All stiffness measures were highly correlated to mobility, load control and comfort dealing with load transfer (Bryant *et al.* 2001).

Figure 5b displays the resultant relative displacement in millimetres between the pack and person for the K, M and F systems. This variable has 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 (Stevenson *et al.* 1995). 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 was among the top 10% of packs in the database.

Figure 6a is a selection of one mean force variable (F_z) and is representative of the all mean 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 (Bryant *et al.* 1996). 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 in the lower half of the database in transmission of vertical (F_z) forces through the spinal column. Although higher mean F_z forces for backpacks might be problematic, basic research studies have shown the tissue tolerance limits for compression of a straight spinal column to be higher than other axes and hence might be able to withstand high forces without injury (Goel *et al.* 1991). Interestingly, all three designs were superior in side-to-side control (F_y, M_x) indicating that soldiers would have better pack control (Bryant *et al.* 1997b). The F model pack was superior in the M_y flexion/extension moment, which would keep spinal shearing forces to a minimum (Reid *et al.* 1999b). This reduced moment was probably caused by the addition of lateral rods into the suspension system that reduced the total bending applied to the spine (Reid *et al.* 2001b). This smaller moment would allow the soldier to stand more upright, thus reducing the load on the erector spinae muscles.

Figure 6b is a representation of force and moment amplitudes of the three CTS prototypes in comparison to database systems. The amplitudes of x, y, z moments in

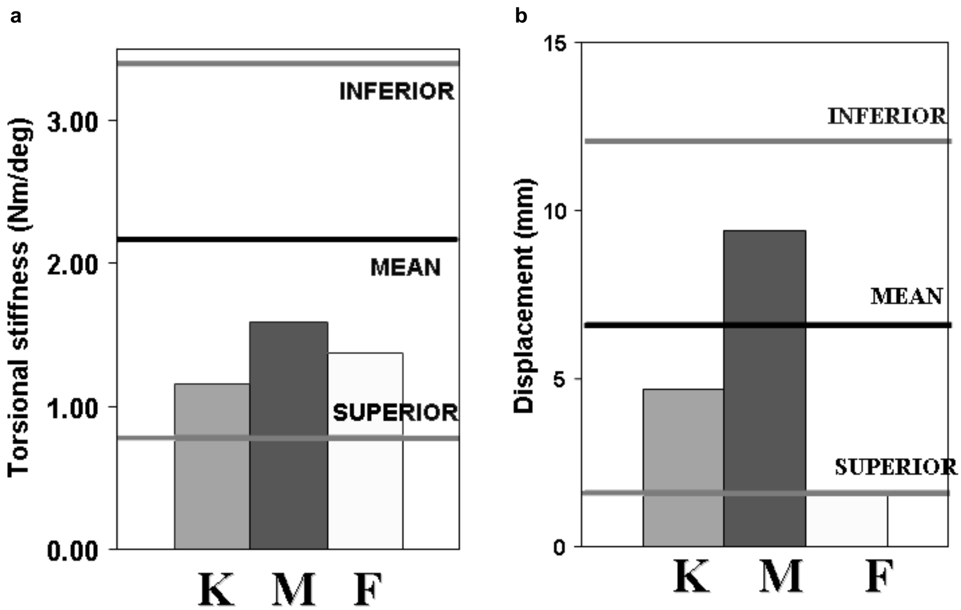

Figure 5. (a) Suspension stiffness from the LC compliance tester. (b) Relative pack displacement from LC simulator.

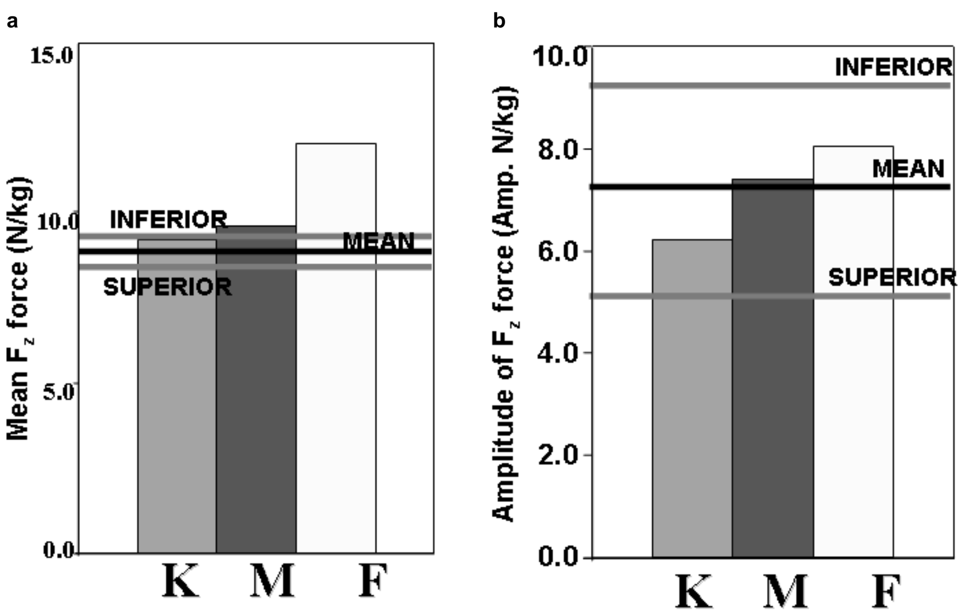

Figure 6. (a) Mean force (F_z) from the LC simulator. (b) Amplitude of force (F_z) from the LC simulator.

Nm/kg and the z and r forces in N/kg were correlated to load control such as balance, mobility, and manoeuvrability (Bryant *et al.* 1996). The three prototypes were consistently below the mean or inferior, indicating that there was a substantial dynamic component experienced by the hips. This was not reflected in the shoulder pressure mean profiles or in the relative displacement of the pack, which indicated that the pack suspension system was absorbing most of the oscillating forces and moments. Kram (1991) proposed 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.* (2001b) found reduced vertical compressive force F_z and increased extension moment M_y on the lumber spine. If these amplitudes can be controlled, then it might be possible to create a tuneable dynamic suspension system. Further research is needed to investigate this hypothesis.

Figure 7 summarizes the pressure profiles experienced by soldiers wearing the prototype systems. Figure 7a indicates the mean anterior shoulder pressure and figure 7b indicates the peak anterior shoulder pressure. Based on previous correlational analyses with soldiers' subjective responses, five shoulder pressure measures and two lumbar pressure measures were related to reports of discomfort (especially in the posterior hip and neck regions) and a reduced ability to doff the pack (Bryant *et al.* 1996). All three design iterations 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 determined in order to reduce lumbar shear and minimize peak loading of the anterior shoulder/axilla region (Reid *et al.* 2001a). In

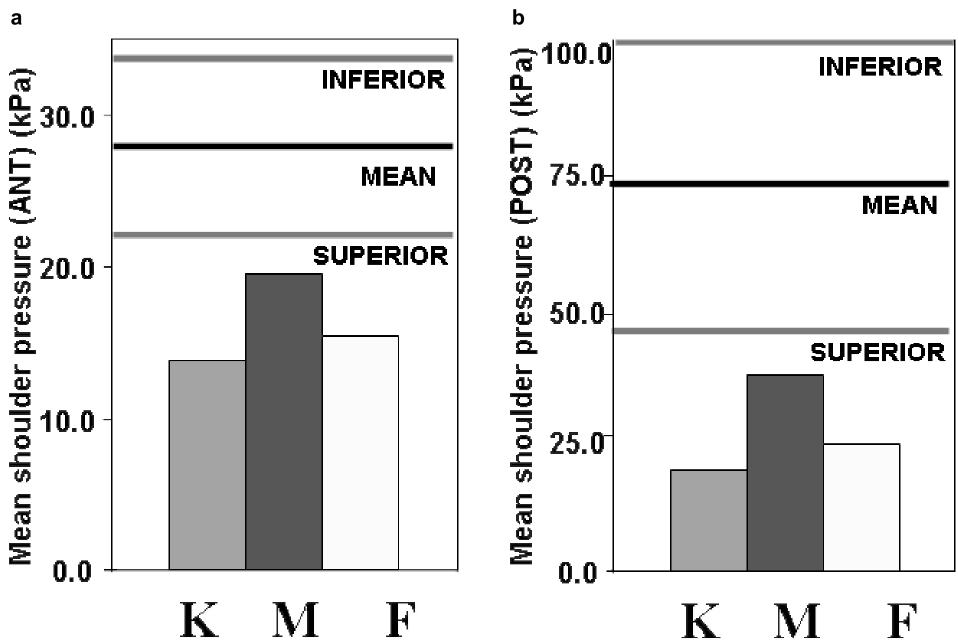

Figure 7. (a) Mean anterior shoulder pressure from LC simulator. (b) Peak posterior shoulder pressure from LC simulator.

the second study, three types of strap shapes were investigated to reduce the contact pressure profiles (Whiteside *et al*. 1999). In addition, the effort to integrate the pack strap configurations with Tactical Assault Vest straps might have contributed to prototypes' superior performances.

5.4. *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 and sternum and hip stabilizer straps. The suspension system was an internal frame system with lateral rods thus possessing some adjustable dynamic characteristics. The internal frame pack and the shorter TAV allowed better manoeuvrability and load control. The pack was integrated well with the TAV because specific interference problems were identified and corrected earlier in the process.

When the results were compared to the benchmark pool, the F model fell into the superior category on 48% of the variables, above the mean on 24%, below the mean on 14% and inferior on 14% of the variables. The pack was in the lowest decile on amplitudes of forces and moments at the level of the hips. These amplitudes were being absorbed by the suspension system, as they did not cause an increase in either the pack motion or pressure at the shoulders. 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 regarding actual use of the LC systems (Stevenson *et al*. 1995, 1997a). In comparison to proposed objective standards, the F model had less than 8 mm of absolute relative motion during walking and lower than 20 kPa of mean pressure at the skin contact surface areas. Peak pressures were under the recommended 35 kPa while carrying a 28.67 kg testing load (Bryant *et al*. 1996, Stevenson *et al*. 2004). The final F model had good control in the relative pack to person motions, mean suspension system stiffness, low mean pressures and peak pressures in the anterior and posterior shoulder regions, mean forces and reaction moments, but higher amplitudes of force and moments at the level of the hips. It was recommended that LC system F be used as the benchmark for future Canadian Forces systems.

6. Overall conclusions and recommendations

DRDC—Toronto developed an ergonomics approach to the development of a new load carriage system for the Canadian Forces whereby ergonomics design principles and user-centred feedback were considered essential to system development. They managed a design team made up of designers and manufacturers, biomechanists and ergonomists and expert military stakeholders to develop the LC system. In a well-orchestrated research and development programme, the team used the biomechanical testing centre at Queen's University to conduct standardized tests on various fragmentation vests, tactical assault vests and rucksack designs. This paper was devoted to describing the processes and biomechanical outcomes that were instrumental in LC system development.

Three iterations of fragmentation vests were studied with differing fastener locations on the shoulders and sides of the trunk as well as one with a neck protection feature. For all vests, the cloth covering material and Kevlar® protection were similar. Results revealed that relative kit motion, and hip reaction force and moments were similar but mean and peak pressures differed between systems. High pressure points were usually a result of seams or folds in the Kevlar® lining. The FV-2 fragmentation vest was recommended with several design changes.

The seven load carriage (LC) vests were evaluated: three short vests, three longer vests and two webbing designs. These LC vests were tested with or without a fragmentation vest worn underneath. Although wearing a fragmentation vest affected the magnitude of the forces and moments, it did not affect skin contact pressures or relative displacements of the kit mass. When LC vests were compared, there were significant differences between specific vests for certain variables. To provide each LC vest with an overall score, they were ranked on each variable from highest to lowest and then rankings were summed. A short vest called SV3 ranked highest and was recommended, conditional on a number of further design changes.

For the backpack or rucksack component, three models were tested over top of the chosen Tactical Assault Vest (SV3). These backpack designs were a single large bag (K model), a modular system (M model) and the final design (F model). Each system was compared to a database of objective biomechanical variables from 17 military and civilian packs. In comparison to the database, the F model ranked above the mean 72% of the time with 48% of variables in the top decile of performance. The F model was particularly effective at reducing skin contact pressures under 15 kPa for mean pressure and 25 kPa for peak pressure as well as reduced pack-person motion to 8 mm. These data would mean that soldiers would have optimal shoulder and waist comfort when carrying heavy loads, and pack control would be optimal as well.

Results of these analyses were confirmed in subsequent field testing with soldiers (Tack and Gaughan 1996, Bossi and Tack 2001). Use of objective biomechanical testing meant that the Canadian LC system progressed from design concepts to final product more quickly, with reduced costs and increased inconvenience without sacrificing accuracy and validity of test results and recommendations. In addition, the standardized system could detect relatively small design differences. This attribute of objective testing is not often accomplished through physiological, biomechanical or perceptual approaches in human testing (Martin and Nelson 1982, Kirk and Schneider 1992). Although design iterations could be tested and feedback given within two weeks, this scientific testing cannot replace human trials for critical design evaluations, especially in relation to pack features and functionality.

The objective biomechanical assessment tools have other advantages as well. They allow for improved understanding of the effects of design features, provide the potential for design comparisons and can provide feedback on particular designs relative to a database of other systems. The tools also allow for the establishment of objective performance criteria (e.g., maximal skin contact pressure or relative pack motion) that could be used as objective standards for military procurement. Because the new Canadian LC system is among the top decile in 48% of objective variables and above average in an addition 24% of variables, it is recommended that this system become the benchmark for feature Canadian LC systems.

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