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A Preliminary Investigation of the Effect of Protective Clothing Weight, Bulk and Stiffness on Combat Mobility Course Performance

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Soldier loads continue to rise in response to new technological capabilities and emerging threats. However, literature addressing the extent to which load mass properties affects operational task performance and mission outcome is sparse. The objective of this preliminary study was to quantify the effect of PPE mass properties (weight, bulk and stiffness) on combat mobility, as measured using the standardized Load Effects Assessment Program (LEAP) course. Twenty-four soldiers completed the LEAP course in three clothing and individual equipment (CIE) configurations (UE: unencumbered; FFO: full fighting order (FFO) without body armour; and FFO+: FFO with body armour). Significant differences between clothing conditions were revealed for LEAP performance metrics (overall course time). Regression analysis revealed significant relationships between overall mobility performance and condition mass properties of weight, bulk, and stiffness. Outcomes will influence the design of future CIE and future research in this area.

INTRODUCTION

Physical overload remains a significant challenge for the modern warfighter. While soldiers have long been required to carry heavy loads (Knapik et. al., 2004), new technologies, shifting demands of asymmetric warfare, reduced confidence in re-supply, and the desire to protect soldiers from emerging threats are contributing to ever-increasing soldier loads that are nearing, if not surpassing body weight (Dean, 2004; US NRAC, 2007).

Many research studies have focused on the effect of carried or worn loads on soldier physiology and biomechanics (Attwells et al., 2006; Beekley et al., 2007; Birrell et. al., 2007). Studies have typically examined the effect of heavy loads carried in backpacks during marching or running tasks, soldier marksmanship, and obstacle course performance (LaFiandra et. al., 2003; Hasselquist et. al., 2008). More recently, researchers have investigated body armour and fighting loads (Hasselquist et. al., 2008 & 2012, Ricciardi et. al., 2008; DeMaio et. al., 2009). Increased load weight has been found to increase physiological strain, alter biomechanics and decrease physical task performance in surrogate tasks.

It has been acknowledged that adequate models that incorporate combat effectiveness parameters (e.g. lethality, survivability) and predict operational task performance effects of weight do not exist (NRAC, 2007). There is even less known of the contributions of other mass properties (e.g., stiffness, bulk), as these are difficult to isolate for study. Particularly poorly understood are the trade-offs between protection, performance, soldier injury, and survivability (Larsen, 2011).

The Load Effects Assessment Program (LEAP) is an instrumented operationally-realistic combat mobility course designed for the United States Marine Corps (Kelly et. al., 2014; Richter, 2014). LEAP comprises 10 sequential timed mobility tasks plus a set of accessory tasks, each designed to simulate the most common or most challenging physical tasks encountered during recent military tactical operations.

The current research is part of larger effort using Canada's LEAP (CAN-LEAP) to parameterize soldier equipment-related contributions to soldier mobility performance. The objective of the current analysis was to assess LEAP sensitivity to relevant differences in soldier clothing and equipment ensembles, and to conduct a preliminary investigation of the relationship between the weight, stiffness and bulk attributes of soldier clothing and individual equipment (CIE) and mobility performance. Each of these parameters is hypothesized to contribute to decrements in mobility performance (i.e., decrease movement speed or increase combat mobility course completion time).

METHODS

Participants completed the LEAP combat mobility course in three CIE conditions in a counter-balanced repeated measures design. All testing was performed indoors under temperate conditions. Participants were limited to two LEAP runs per day, with a minimum one-hour rest between runs. Measures for each condition included: overall course and individual obstacle completion time; load weight; range of motion (ROM); and anthropometric measures of encumbered soldier torso bulk. DRDC's Human Research Ethics Committee (HREC) approved the research protocol.

Participants

Data were gathered from 24 infantry and combat engineer soldiers of the Canadian Armed Forces (CAF). The male study population averaged 178.5 ± 6.8 cm for stature, 84.0 ± 12.5 kg for body weight, 26.3 ± 3.1 kg/m^2 for body mass index, 26.8 ± 3.5 years for age, and 48.9 ± 3.3 mL/min/kg for predicted VO_2 max. On average, participants had 5.2 ± 1.5 years of regular service. Eighteen participants had deployment experience (8.5 ± 3.9 months) and all were experienced wearing body armour in training or operations.

Load Effects Assessment Program (LEAP)

The timed portion of LEAP comprises ten sequenced obstacles or tasks. Obstacles included: 1) Hatch and Tunnel: representing a typical vehicle hatch opening and roadway culvert; 2) Sprint: representing a run between points of cover; 3) Stairs and Ladders: representing those encountered in urban operations; 4) Agility Run: representing a run through complex terrain; 5) Casualty Drag: representing a rescue operation; 6) Windows: representing typical non-door room entries; 7) Bounding Rushes: representing typical team fire and movement; 8) Uneven Balance Beam: representing uneven and narrow traverse; 9) Crawl: representing movement in confined spaces; and 10) Courtyard Walls. A networked RFID system, with back-up manual stopwatch timing, recorded total course and individual obstacle completion times.

Test Conditions

Participants donned three levels of Canadian Armed Forces (CAF) personal protective equipment for dismounted combat soldiers, hereafter termed soldier clothing and individual equipment (CIE). The test conditions are outlined in Table 1 below and illustrated in Figure 1.

Table 1. Description of test conditions and load weights (M ± SD).

Unencumbered (UE): combat clothing (shirt and trousers), temperate gloves, kneepads (optional, but consistent across conditions), combat boots, ballistic eyewear (BEW).	4.8 kg ± 0.86
Full Fighting Order (FFO): Condition UE plus C7A2 assault rifle, CG639 ballistic helmet, and Tactical load-bearing Vest with ammunition, water, first aid and communications.	18.3 kg ± 0.78
FFO plus ballistic protection (FFO+): Condition FFO plus Fragmentation Protective Vest (soft armour) and ceramic (hard armour) plates (front and back).	25.7 kg ± 1.0

Procedure

Following an introductory briefing, medical screening, informed voluntary consent and participant characterization (demographic questionnaire, predicted VO_2 max test, anthropometric measurements), the LEAP course was demonstrated. On the first day, participants familiarized themselves with LEAP and completed two runs while wearing first the UE and then FFO+ test condition. On subsequent test days, participants completed their assigned CIE conditions (counter-balanced across participants). Participants were limited to two LEAP runs per day, with a minimum one-hour rest between runs (heart rate within 10% of resting). Prior to each LEAP run, participants donned a Polar® heart rate monitor prior to dressing in their assigned test condition.

Figure 1. CIE Conditions UE, FFO and FFO+ *(above)*. Canadian Tactical Vest, Fragmentation Protective Vest (soft armour) and ceramic plates (hard armour) *(below)*.

Weight
The mean weights of the CIE load conditions are documented in Table 1. The weight of a participant wearing the assigned CIE was recorded prior to the start of each LEAP run. Condition load weight variable is defined as the delta between total weight and participant body weight.

Bulk
As a measure of bulk, participant anthropometric measurements (semi-nude and encumbered) were recorded for each CIE condition. A manual encumbered anthropometric protocol was developed for this study (Jones et. al., 2013). Manual measures were obtained using two different land-marking paradigms: 1) *Normalized to anthropometric landmarks* involved taking individual breadth, depth and circumference measurements at cross-sectional heights associated with anatomical landmarks on the torso (e.g. deltoid point, chest, and waist), and 2) *Maximal bulk*, wherein breadth, depth and circumference measures were acquired at the point of maximal bulk or girth for a specified region of the encumbered torso (e.g. over-shoulder, upper torso, mid-torso, and lower torso), as were the heights at which those occurred. Unencumbered measures were retaken at each point of

maximal bulk and corresponding height to provide an equivalent measure at each cross-sectional height.

Stiffness

Functional range of motion (ROM) assessments that target trunk ROM were performed for each CIE condition. ROM measures included: Trunk Forward Flexion: participants sat with legs fully extended, and reached forward; Trunk Lateral Flexion (Left, Right): participants bent trunk laterally to the side in the frontal plane; Trunk Rotation (Left, Right): participants assumed a forward flexed posture bending about the lumbar spine. All ROM measures were performed to a participant volitional maximum.

Data Analysis

Repeated measures ANOVA were used to evaluate differences in LEAP performance measures. Given the large number of hypotheses being tested, a conservative *p*-value of 0.001 was used. Duncan post hoc tests were performed for all pairwise contrast tests. Greenhouse-Geisser adjustments were considered for violation of sphericity. An alpha level of 0.05 was adopted by all pairwise analyses. Linear regression analysis was conducted to assess the effects of condition mass properties on LEAP performance.

RESULTS

Overall LEAP Course Completion Time

Figure 2 shows the main results for overall course completion time by CIE condition. Mean course completion times (± SD) were: UE: 206.6 ± 27.6 FFO: 283.2 ± 39.5 FFO+: 317.2 ± 46.8. Repeated measures ANOVA with Duncan post hoc tests determined that all three conditions were significantly different from one another (n=23, F(2,44)=185.26, p≤0.001; UE < FFO < FFO+, p ≤ 0.05). The same finding held true for most of the individual obstacles or tasks (range of F values and degrees of freedom, p≤0.001, detailed statistics available from the lead author). For three of the obstacles; specifically, Stairs and Ladders, Casualty Drag, Courtyard Walls, significant differences were not found in performance between Conditions FFO and FFO+.

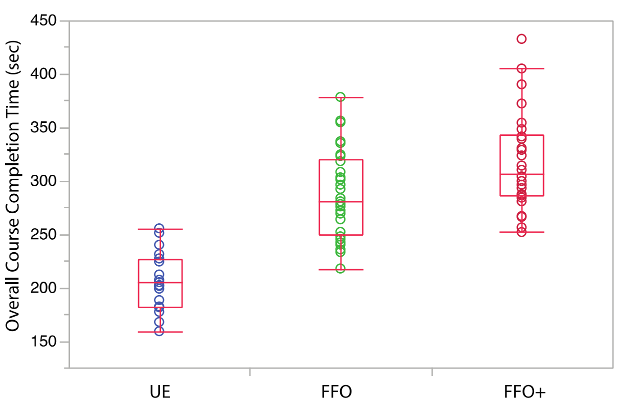

Figure 2. Overall LEAP course completion times by CIE condition (n=23, F (2,44)=185.26, p ≤ 0.001; UE< FFO < FFO+, p ≤ 0.05). Test conditions coded by color: UE –blue (O), FFO –green (O), FFO+ -red (O).

Condition Mass Properties

Repeated measures ANOVA and pairwise contrast test found that condition load weight (both absolute and as % of body weight) differed significantly across all CIE conditions. Depth measures of bulk obtained at both Normalized and Maximal landmark paradigms were found to differ significantly for all CIE conditions, with the exception of waist depth measure, which did not differentiate between FFO and FFO+. All of the breadth measures of bulk varied significantly for UE vs. the encumbered CIE conditions. However, the mid-torso breadth was the only measure that was sensitive to the differences between the FFO and FFO+ conditions. Stiffness measures were more variable. With the exception of the lateral flexion (left) measure, all of the ROM measures were sensitive to differences between UE and encumbered CIE conditions. ROM measures did not differ between the FFO and FFO+ conditions.

Effect of Weight on Mobility Performance

Figure 3 shows the correlation between total LEAP course time and condition weight. Results indicate a significant positive correlation between course completion time and load weight, either absolute (R^2 = 0.61, RMSE = 38.3), or when expressed as a proportion of participant body weight (R^2 = 0.58, RMSE = 39.7). As condition weight increases, overall course time also increases.

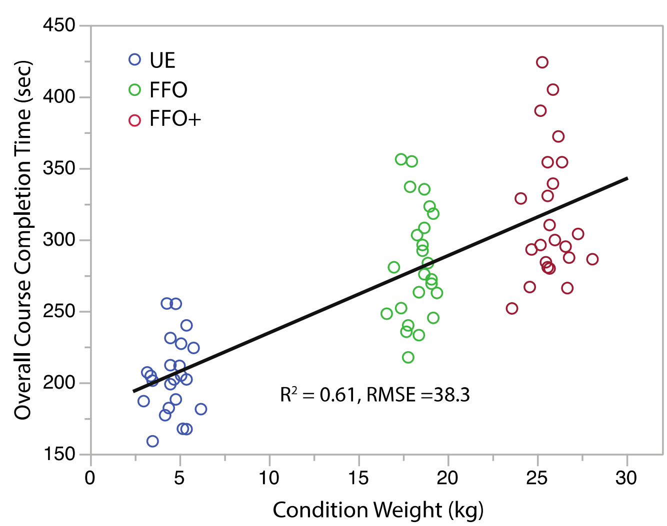

Figure 3. Relationship between overall LEAP course time (CT) and CIE Condition load weight (CW). CT = 165.62 + 5.82*Condition Weight. Test conditions coded by color: UE –blue (O), FFO –green (O), FFO+ -red (O).

Effect of Bulk on Mobility Performance
Results indicate a significant positive correlation between course completion time and all of the normalized and maximal bulk anthropometric measures. Figure 4 shows the relationship between course LEAP completion time and the maximal bulk measure defined at the upper torso region (R^2 = 0.64, RMSE = 32.6). Table 2 shows the regression results for breadth and depth measures of bulk, defined by both the Normalized to Anthropometry and Maximal Bulk paradigms (Jones et al., 2013). As bulk increases, particularly around the chest, mobility course completion time increases.

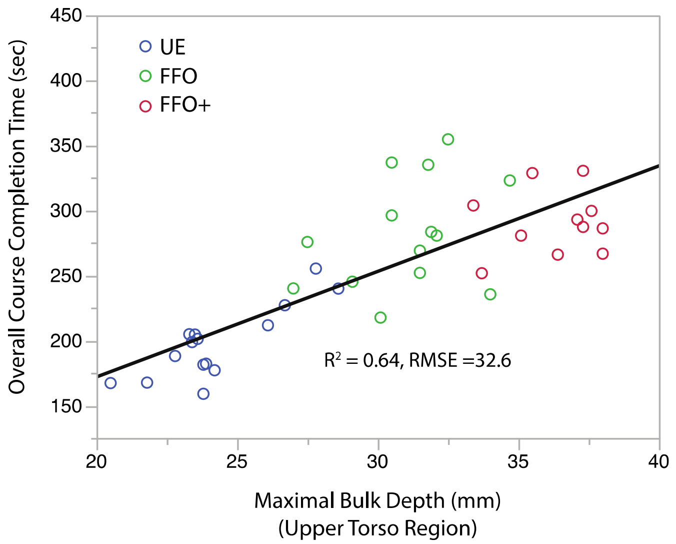

Figure 4. Relationship between overall LEAP course time (TT) and maximal bulk depth measure at the Upper Torso region of the CIE. TT = 9.46 + 8.12*UpperTorso_Depth. Test conditions coded by color: UE –blue (O), FFO –green (O), FFO+ -red (O).

Table 2. Effects of Normalized and Maximal Bulk defined breadth and depth measures on overall LEAP performance time (TT). Normalized Bulk: Deltoid, Chest, and Waist. Maximal Bulk (shaded): Over Shoulder, Upper Torso, Mid Torso, and Lower Torso regions of the CIE.

	Regression Equation	RSME	R^2
Deltoid	TT = -152.93 + 8.29*Deltoid _Brdth	53.6	0.17
Chest	TT = -43.99 + 8.87*Chest_ Brdth	52.1	0.22
Waist	TT = 128.08 + 3.16*Waist_Brdth	47.3	0.36
UpT	TT = -84.71 + 9.57*UpperT_Brdth	42.4	0.40
MidT	TT = 43.65 + 5.61*MidT_Brdth	42.5	0.48
LowT	TT = 99.44 + 3.73*LowT_Brdth	43.6	0.45
Deltoid	TT = 25.76 + 8.65*Deltoid _Depth	43.4	0.48
Chest	TT= 4.86 + 8.60*Chest_Depth	36.9	0.61
Waist	TT= 105.48 + 5.38*Waist_Depth	39.8	0.55
OverSh	TT = 34.19 + 7.94*OverSh_Depth	44.9	0.42
UpT	TT = 9.46 + 8.12*UpperT_Depth	32.6	0.64
MidT	TT = 43.93 + 7.42*MidT_Depth	36.7	0.61
LowT	TT= 18.38 + 8.45*LowT_Depth	40.8	0.52

Effect of Stiffness on Mobility Performance
Results indicate a significant negative correlation between course completion time and most ROM measures: Trunk Rotation-Left (R^2 = 0.24, RMSE = 52.3); Trunk Rotation-Right (R^2 = 0.18, RMSE = 54.6); and Trunk Forward Flexion (R^2 = 0.10, RMSE = 57.2). Figure 5 shows the negative relationship for one measure of trunk ROM (Trunk Rotation-Left). As range of motion decreases (or CIE stiffness increases), overall course completion time increases.

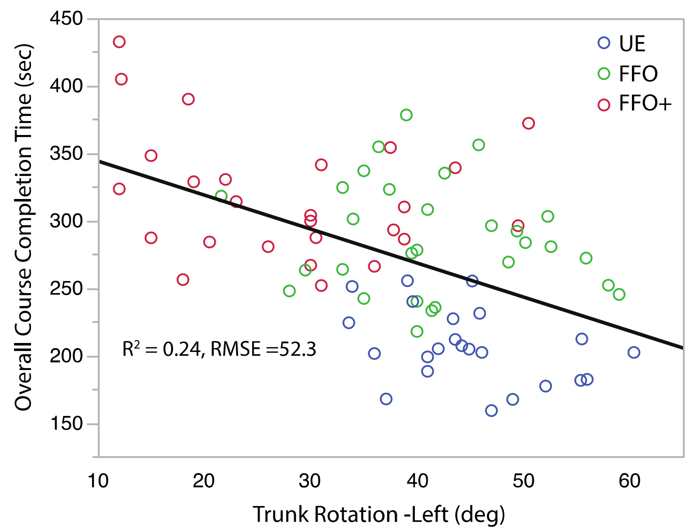

Figure 5. Relationship between overall LEAP course time (TT) and Trunk Rotation -Left (Rot-Lt). TT = 369.21- 2.52* Rot - L. Test conditions coded by color: UE –blue (O), FFO –green (O), FFO+ -red (O).

DISCUSSION

This study is the first in a series of CAN-LEAP studies that quantify the effect of soldier clothing and equipment ensembles on operationally-relevant combat mobility tasks. A second objective was to evaluate the relationship between the load parameters of weight, bulk, and stiffness and combat mobility performance. As hypothesized, the heavier the load, the more time required to complete the overall LEAP mobility course and individual components. LEAP performance was also sensitive to differences in measures of bulk. Both the Normalized and Maximal bulk measures were found to be factors in determining overall LEAP performance, as overall course time was found to degrade with increased bulk measures of load distribution. Most of the stiffness (ROM) results indicate an impact of torso-borne load stiffness on mobility performance. As more and more equipment is worn on the torso, range of motion, particularly trunk rotation, is reduced and contributes to increased course completion times.

Knowledge that individual objective measures of encumbrance (load weight, bulk, and stiffness) are sensitive to differences in equipment and somewhat predictive of dismounted mobility performance can inform future CIE requirements, design, test and evaluation as well as inform eventual models that take into account mobility performance impact on mission outcomes such as lethality and survivability. These physical attributes can be difficult to isolate or evaluate in terms of their individual contribution to performance and mobility. Knowledge about performance degradation or costs of the cumulative or interdependent effects of these physical stressors on soldier performance is critical.

Is the mobility decrement observed in this study operationally relevant? In the absence of published data, it seems reasonable to suggest that if soldiers take longer to perform operationally-relevant tasks (i.e., as represented by the individual components of LEAP), they may be exposed longer and thus may be more susceptible to enemy action.

CONCLUSIONS

LEAP appears to be a useful tool for assessing the mobility impact of alternative realistic soldier system ensembles. For research purposes, more work is needed to develop and validate protocols for reliably outfitting participants in their protective gear, and for more accurate and reliable measurement of ensemble stiffness or encumbered soldier range of motion. Future studies should also take advantage of rapid 3D body scanning technologies for more efficiently and reliably capturing encumbered bulk data.

Ongoing and future LEAP studies by Canada will examine more operationally-realistic (i.e., heavier) loads, loads more representative of all infantry roles (e.g., rifleman, grenadier, machine gunner, section commander), and the impact of systematically altering the load characteristics, independent of each other, to the extent that is possible. Loads that represent a wider range of weight, bulk, stiffness and load distribution (e.g., worn versus carried, extended body coverage armour) will be examined so that we may begin to model the relative contributions of mass properties for a wider range of soldier equipment to mobility performance. Finally, it will be important to relate mobility decrements to susceptibility or vulnerability to enemy fire, so that the impact of load on survivability may be better understood, and decision tools developed to assist in decision making about the most appropriate context for use of heavy protective gear such as hard body armour.

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