Published online: 1-21-2014

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Recommended Citation

Park, Huiju; Branson, Donna; Petrova, Adriana; Peksoz, Semra; Goad, Carla; Warren, Aric J.; Jacobson, Bert; and Kamenidis, Panagiotis (2014) "Effects of Body Armor and Load Carriage on Lower Limb Joint Movement," *Journal of Human Performance in Extreme Environments*: Vol. 10 : Iss. 2 , Article 3.

DOI: 10.7771/2327-2937.1049

Available at: <https://docs.lib.purdue.edu/jhpee/vol10/iss2/3>

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Abstract

This study investigated the impact of body armor weight and load magnitude and distribution on the lower extremities during walking. Range of motion (ROM) was assessed while seven healthy, male, right-handed, military university students walked while wearing seven different garments of varying weights (0.06 kg, 9 kg, 18 kg, and 27 kg) and load distributions. Decreased pelvic rotation found with an increase in weight implies decreased mobility by restricting the leg's swing to propel the body forward. Increased ROM for pelvic tilt found with increased weight results from increased forward inclination suggesting an increased possibility for fatigue and musculoskeletal pain in the lower back. This study substantiated that a balanced weight distribution can minimize risk of chronic lumbar pain by reducing forward lean of the trunk or pelvic tilt; a balanced weight distribution around the torso at a level of 27 kg showed less change in ROM for pelvic tilt than an unbalanced weight distribution.

Keywords: body armor, load, motion, joint, legs, mobility, design

1. Introduction

One of the key factors affecting human motion is the amount of weight carried. In particular, weight bearing affects mobility and work efficiency of soldiers because wearing heavy body armor and carrying load are essential to their missions as well as to their safety. Armor weight has become a major concern of the military which desires maximum mobility and work efficiency for soldiers in combat zones (Bonsignore, 2006). According to Leimbach (2006), an infantry soldier typically carries 45 to 68 kg of items in addition to body armor. Konitzer, Fargo, Brininger, and Reed (2008) claimed that increased weight of body armor has led to an increase in the reported incidence of musculoskeletal pain such as knee pain, stress fractures, and lower back injuries. Roy, Lopez, and Piva (2013), in their survey study with 805 soldiers deployed to Afghanistan, reported that about 20% of the soldiers experienced lower back injuries that relate significantly to wearing body armor and carrying load. Attwells, Birrell, Hooper, and Mansfield (2006) also showed that carrying heavy military load causes musculoskeletal pains because of increased muscle strain and tensions owing to changes in the body posture necessary to counterbalance the changes in the position of the center of mass that happens when additional weight is placed around the torso. These previous studies indicate negative impacts of military load carriage on soldiers' musculoskeletal health and safety.

In addition, maintaining mobility while carrying equipment is critical for the success of a military operation and work efficiency. In particular, mobility of the lower limbs is crucial to individual performance and safety of soldiers during military operations because walking and running are quintessential ways of locomotion in a combat zone particularly for infantry soldiers (Man, Swan, & Rahmatalla, 2006). A typical repetitive activity of soldiers is walking while wearing a heavy ballistic vest with an attached personal load. Recent studies (Bastien, Willems, Schepens, & Heglund, 2005; Griffin, Roberts, & Kram, 2003; Laing Treloar & Billing, 2011; Pandolf, Givoni, & Goldman, 1977) have reported that weight bearing affects soldiers' mobility and increases energy expenditures, causing rapid fatigue. Laing Treloar and Billing (2011) reported that military load carriage significantly lowered the speed of running by increasing metabolic cost. The negative

impact of the physical burden resulting from carrying load was greater for female soldiers than for males. An increase in carrying load elevates metabolic cost when soldiers are standing and walking, and an increase in walking speed accelerates the energy expenditure (Pandolf et al., 1977). Bastien et al. (2005) further discovered that the metabolic cost increases curvilinearly with walking speed and linearly with the weight of the load. Based on this relationship, they further suggested an optimal loading (25% of body mass) for a long-distance march. Increased metabolic cost while carrying a load is incurred when the foot is in contact with the ground. A study by Griffin et al. (2003) established that a majority of increased metabolic cost while walking and carrying load is largely explained by increased muscular force during the stance phase while preparing for the swing phase.

The distribution of load can be a significant moderator for impacts of load on energy expenditure and lower body movement. Birrell and Haslam (2010) found that weight distribution is a significant factor in changes in gait pattern and energy expenditure. Their study discovered that placing the load on the back displaces the body's center of mass further away from its original position (inside the pelvis), which results in increased maximum braking force. This can be a direct cause of blisters and increased energy expenditure. Grenier et al. (2012) also found significant changes in gait mechanics in loaded conditions. However, they did not find an increase in energy expenditure in loading conditions where the center of mass is moved away from its neutral position. These two studies with inconsistent findings imply a need for further research into the impact of weight distribution on metabolic cost.

Since a frontline combat zone is no longer the norm in modern warfare, wearing body armor and carrying load is typical for any soldier. It is important to note that no study has examined the potentially synergistic impact of wearing body armor with load carriage on lower body movement. Although previous studies have identified negative impacts of carrying load, those studies tended to focus on energy expenditure changes related to load increase. In addition, our review of the literature suggests a need for an understanding of the impact of load distribution on soldiers' body movement. Considering the high risk of musculoskeletal injury when walking on an unfavorable terrain while wearing heavy body armor and carrying load, the investigation of lower limb dynamics is warranted. This research gap highlights the need to examine the impact on lower body motion of wearing body armor with an attached load—the focus of this research. Specifically, this study analyzed range of motion (ROM) as a kinematic variable of lower body motion during walking. ROM was measured for various levels of load including a standard body armor outer tactical vest (OTV) as well as additional loads. The placement of the additional loads was varied to create

different load distribution configurations. The following two hypotheses were tested:

- 1) H_{01} : There will be no significant difference in lower body ROM during walking for different load levels.
- 2) H_{02} : There will be no significant difference in lower body ROM during walking for different weight distribution configurations.

The Davis protocol for marking the body in order to perform movement analysis has been widely used in podiatry and orthopedics to identify changes in gait pattern because of its effective data reduction necessary for gait analysis (Davis, Ounpuu, Tyburski, & Gage, 1991; Park, 2011; Park et al., 2011). The Davis protocol was used for data collection in this study.

2. Methods

2.1. Subjects Sampling for Human Performance Test

Approval of the study protocol was obtained from the Oklahoma State University Institutional Review Board prior to recruiting volunteers. Nine healthy male right-handed ROTC university student volunteers were recruited. Right-handedness was required in order to control for possible influence of dominance on movement patterns in this study. Participants had to be within a certain body size in order to fit the medium issue size OTV, which was available for the study.

To ensure an appropriate fit of the OTV on each participant's torso, the researchers visually assessed the fit of the vest based on the following requirements:

- 1) The OTV must cover the torso area down to the bottom of the ribcage but not cover the waistline of the subject where markers will be placed during the experiment.
- 2) Using the adjustable Velcro straps, the OTV must be fitted snugly (not being tight or loose) around the subject's torso without leaving any areas on the side of the body uncovered.
- 3) The OTV armhole must not interfere with the natural swing of the arm, which occurs if the armhole is too small or too high in the underarm area.

One of the nine volunteers was excluded because the test vest did not properly fit his body. Another volunteer was not accepted because of his age (37 years old); other subjects were younger (mean age: 21.3 ± 1.1 years). Finally, the study included seven right-handed participants with an average age of 21.3 ± 1.1 years, average height of 183 ± 4.8 cm, and average weight of 91 ± 11 kg. All participants were Caucasian and had prior experience in wearing a ballistic vest and had no history of any orthopedic disorders. Before beginning the series of human performance tests, each participant reviewed the informed

consent form and signed it as an agreement of voluntary participation.

2.2. Variables

2.2.1. Independent variable

The synergistic impact of weight and weight distribution was explored using garment condition as the independent variable. Seven garment conditions were developed at four weight levels, 0.06 kg, 9 kg, 18 kg, and 27 kg, where the 18 kg and 27 kg weight levels were achieved by placing additional loads in various locations on the test vest. Condition 1 (C1), used as the baseline, was a pair of snugly fitting 0.06 kg sports shorts (see Figure 1a). Condition 2 (C2) required additionally wearing a medium-size 9 kg OTV (see Figure 1b), which includes front and back ceramic plates (see Figure 1c).

The OTV, developed by the U.S. Army, was the standard vest issued to the U.S. Army and the U.S. Marine Corps for the first six to seven years of the Iraq and Afghanistan wars. It consists of Cordura® outer and inner shells, multiple layers of Kevlar® soft armor inserts, and two ceramic plates. It includes webbing on the front and back (often referred to as a ‘Molle® system’) designed for load carriage. In this study, separate Molle® pouches containing loads of appropriate weight were attached to the vest in different locations.

To simulate carrying small combat items (ammunitions, grenades, etc.) on the front torso, which is a typical practice for quick reaction in combat situations, conditions C3, C4, and C5 included a low additional load of 9 kg attached to the front of the OTV, raising the total weight (vest and load) to 18 kg. In C3 (see Figure 1d) the load was attached

to the left vest front, while in C4 (see Figure 1e) it was attached to the right vest front. In C5 (see Figure 1f) the same load was evenly distributed to the left (4.5 kg) and right fronts (4.5 kg).

To simulate carrying greater weight, conditions C6 and C7 included an 18 kg load attached to the OTV, or a total of 27 kg with the OTV. For C6 (see Figure 1g), four Molle® pouches containing 4.5 kg each were attached to the vest front (left and right) and back (left and right). In C7 (see Figure 1h), two Molle® pouches containing 9 kg each were attached to the vest back (left and right).

2.2.2. Dependent variable: ROM

ROM is defined by Kreighbaum and Barthels (1996, p. 64) as “the total amount of angular displacement through which two adjacent segments may move.” Therefore, ROM was expressed as the range of the joint angle during movements at each joint. Lateral movements, such as pelvic obliquity and hip abduction–adduction, were captured in the frontal plane. Anterior–posterior movements such as pelvic tilt, hip flexion–extension, knee flexion, and ankle dorsiflexion–plantarflexion were captured in the sagittal plane. Finally, the transverse plane captured intra- and extra-rotational movements at the pelvis, hip, knee, and ankle.

2.3. Walking Test for Measurement of ROM

The BTS Smart-D Motion Capture System® (BTS Bioengineering, Milano) was used to record and measure body movement. The system included spherical retro-reflective markers with adhesive surface, infrared cameras, and a processing computer. The markers were attached to

Figure 1. Conditions 1 through 7.

22 anatomical points on the body of each subject as depicted in Figure 2.

For all garment conditions except C1, the OTV was donned on the subject's body and the researchers ensured that a snug fit consistent for all subjects was achieved by adjusting straps and Velcro® closures, thereby controlling for the possible influence of garment fit. For C3 through C7, after donning the vest, Molle® pouch(es) containing the appropriate test load for each condition were attached to the webbing in a consistent manner for all subjects. The researchers ensured that pouch(es) were securely attached. After marker placement and OTV donning, subjects walked barefoot for approximately twenty feet linearly, in a designated walking area of approximately 5 m × 5 m, at a self-preferred speed. Each subject repeated the walking test five times for each garment condition (C1–C7). Average walking speed ranged between 0.98 m/s and 1.06 m/s for the seven garment conditions.

Eight infrared cameras recorded the location of all markers during walking. A processing computer defined a cycle of walking based on data captured during four

subsequent steps (two for the left leg and two for the right leg). The BTS system used in this study calculated a single outcome measure for both the left and the right legs by averaging the two steps for each leg. Therefore, each trial had a single measure for the left leg and a single measure for the right leg. This trial was evaluated five times; thus there are five subsamples per order/garment/side combination. Upon completion of each walking test, the subject returned to the starting point to prepare for the next test.

The order of wearing the garment conditions was determined using a Latin square design. To avoid fatigue caused by weight bearing, a resting time between trials was allowed as follows, depending on the weight level: two minutes of rest after C1 (0.06 kg) and C2 (9 kg), three minutes after C3, C4, and C5 (18 kg each), and five minutes after C6 and C7 (27 kg each). Different resting times were prescribed so that subjects could recover for the next trial without fatigue from the previous one. Each measurement was performed five times, yielding five measures for the left leg and five for the right leg.

Note: Acromion^a: The projection of the scapula (the shoulder blade) that forms the point of the shoulder.

Sacrum^b: The large heavy bone at the base of the spine, which is made up of fused sacral vertebrae and is located in the vertebral column, between the lumbar vertebrae and the coccyx.

ASIS^c: Anterior superior iliac spine, Extremity of the iliac crest of the pelvis, which provides attachment for the inguinal ligament, sartorius muscle, and tensor fasciae latae.

Great trochanter^d: A large, irregular, quadrilateral eminence of femur

Femoral condyle^e: The rounded projected articular area in femur

Lateral malleus^f: Bony prominence on each side of the ankle

Figure 2. Marker placements.

2.4. Data Analysis

A processing computer of the BTS system calculated dependent variables. ROMs for each lower body joint were used for data analysis. There were five subsampling measurements on each side, and these were averaged for each subject/garment condition. A total of 98 walking tests (7 subjects $\times$ 7 garment conditions $\times$ 2 sides) were analyzed. Mixed models repeated measures analysis (where side is the repeated measure) was performed using either the SAS/MIXED[®] procedure or SAS/GLIMMIX[®] procedure, Version 9.2 of the SAS System (SAS Institute Inc., 2010). Fixed effects included order, garment, and side main effects along with garment by side and order by side interactions. Subjects were random effects in the analysis. Kenward–Roger df adjustment methods were used in the repeated measures analysis.

The experimental design was a crossover design with two repeated measures. The participants and the order of testing garment conditions were blocks and the side defined the repeated measures. An assessment was made of the main effects of order, garment, and LR (left and right side) and the potential interactions. Post-hoc tests of the garment conditions using Tukey pairwise comparisons and trend analysis of the carrying load were conducted when a garment effect was considered significant. Four levels of garment weight (C1 at 0.06 kg, C2 at 9 kg, C3, C4, and C5 at 18 kg, and C6 and C7 at 27 kg) were contrasted using orthogonal polynomial contrasts during trend analysis. All statistical tests were done at the 0.05 level of significance.

3. Results

Results of the statistical analysis are summarized in Table 1. No significant interaction between side and garment was found at any joint, which indicates that the trend of ROM at all joints was consistent across garment conditions. Therefore, further comparison of bilateral kinematic measures within each garment condition was not performed.

3.1. ROM in Frontal Plane Movements

Pelvic obliquity. A significant garment effect ($p = 0.0022$) was found. As indicated in Table 1, post-hoc tests showed a significant difference ($p \leq 0.0405$) in ROM for pelvic obliquity between C1 and C3, C1 and C5, and C2 and C3. ROM for pelvic obliquity tended to decrease ($p = 0.0004$) with increasing weight of garment and load, across four levels of weight, as shown in Figure 3a.

Hip adduction–abduction. There was a significant garment effect ($p = 0.0239$). ROM for hip adduction–abduction ($p = 0.0457$) was smaller for C3 (11.78°)

compared to C1 (13.37°). There was no significant linear trend of this decreased ROM for hip adduction–abduction (see Figure 3b).

Knee varus–valgus. There was no significant garment effect (Table 1).

3.2. ROM in Sagittal Plane Movements

Pelvic tilt. A significant garment effect ($p < 0.0001$) was found. ROM for pelvic tilt tended to increase with weight. It was highest with C7 (4.61°) compared to the rest of the garment treatments ($p \leq 0.0006$), as evident from post-hoc tests. A significant linear trend was recorded across four levels of weight of garment and carrying load ($p = 0.047$) (see Figure 4a). Finally, ROM on the left side was greater (3.58°) than on the right side (3.36°) ($p = 0.0301$).

Hip flexion–extension. As expected, the garment effect was significant ($p = 0.0272$). ROM for hip flexion–extension was much larger for C7 (44.86°) as compared to C1 (40.99°) and C4 (40.89°). A linear trend of increased ROM for hip flexion–extension was present across four levels of garment weight and carrying load ($p = 0.0252$) (see Figure 4b).

Knee flexion and ankle flexion. Neither garment nor LR effect was significant (Table 1).

3.3. ROM in Transverse Plane Movements

Pelvic rotation. There was a significant garment effect ($p = 0.0027$). ROM for pelvic rotation was significantly higher for C1 (9.56°) than for C2 (6.77°), C4 (6.98°), C5 (6.396°), C6 (6.48°), and C7 (5.94°) as shown in Table 1. Overall, ROM for pelvic rotation tended to decrease with increasing weight. It was also higher on the right side (7.389°) than on the left side (6.789°) ($p < 0.001$), while there was a significant linear trend ($p = 0.0001$) across four levels of weight of garment and carrying load, according to the trend analysis (see Figure 5a).

Hip rotation. A significant garment effect was demonstrated for the hip rotation ROM ($p = 0.0062$). However, the trend for hip rotation was not linear with an increase in carrying load. ROM for C7 was higher (14.82°) than that for C3 (12.18°), C4 (12.52°), and C5 (12.74°). As indicated in Table 1, there was a significant mean difference, verified by post-hoc tests. Finally, subjects showed significantly larger ROM on the left side (14.66°) compared to the right side (11.97°) ($p < 0.0001$) (see Figure 5b).

Knee rotation. No garment effect was observed. However, ROM was notably greater on the right side (25.13°) than on the left side (22.52°) ($p = 0.004$) as shown in Table 1.

Ankle rotation. A significant order effect relative to ankle rotation was measured ($p = 0.0161$) as shown in Table 1. Neither garment nor LR effect was present.

Table 1

ROM least squares means, standard errors, and significance levels for garment and LR (left and right side) effects.

Garment Effect		Garment treatments							p-value
		C1	C2	C3	C4	C5	C6	C7	
Total weight (kg)		0.06	9	18	18	18	27	27	
Weight distribution
		LSMean	LSMean	LSMean	LSMean	LSMean	LSMean	LSMean	
*Pelvic obliquity		6.16 ^a	6.08 ^{ab}	4.48 ^c	4.87 ^{abc}	4.65 ^{bc}	4.74 ^{abc}	5.16 ^{abc}	0.0022
	Std Error	0.51	0.51	0.51	0.51	0.54	0.57	0.54	
*Hip adduction-abduction		13.37 ^a	13.19 ^{ab}	11.78 ^b	12.19 ^{ab}	12.3 ^{ab}	12.89 ^{ab}	13.11 ^{ab}	0.0239
	Std Error	0.65	0.65	0.65	0.65	0.65	0.65	0.65	
Knee varus-valgus		10.27	11.66	11.81	10.42	10.57	10.78	10.86	0.4185
	Std Error	1.46	1.46	1.46	1.46	1.46	1.46	1.46	
*Pelvic tilt		3.36 ^b	3.34 ^b	3.404 ^b	3.35 ^b	3.19 ^b	3.05 ^b	4.61 ^a	<.0001
	Std Error	0.2	0.2	0.2	0.2	0.21	0.23	0.21	
*Hip flexion-extension		40.99 ^b	42.58 ^{ab}	41.44 ^{ab}	40.89 ^b	41.704 ^{ab}	42.99 ^{ab}	44.86 ^a	0.0272
	Std Error	1.5	1.5	1.5	1.5	1.5	1.5	1.5	
Knee flexion		58.24	58.46	57.90	57.77	58.27	58.46	57.62	0.97
	Std Error	1.69	1.69	1.69	1.69	1.69	1.69	1.69	
Ankle dorsiflexion-plantarflexion		30.44	31.46	30.42	29.22	30.39	30.19	30.54	0.13
	Std Error	1.23	1.23	1.23	1.23	1.23	1.23	1.23	
*Pelvic rotation		9.56 ^a	6.77 ^b	7.5007 ^{ab}	6.98 ^b	6.396 ^b	6.48 ^b	5.94 ^b	0.0027
	Std Error	0.9	0.9	0.9	0.9	0.94	0.99	0.94	
*Hip rotation		14.04 ^{ab}	13.37 ^{ab}	12.18 ^b	12.52 ^b	12.74 ^b	13.52 ^{ab}	14.82 ^a	0.0062
	Std Error	0.97	0.97	0.97	0.97	0.97	0.97	0.97	
Knee rotation		23.51	24.97	24.71	22.86	23.44	24.04	23.24	0.1577
	Std Error	1.78	1.78	1.78	1.78	1.78	1.78	1.78	
Ankle rotation		15.73	16.101	15.27	14.79	15.63	16.68	16.44	0.13
	Std Error	1.74	1.74	1.74	1.74	1.75	1.76	1.75	
Side Effect									
		Right		Left				p-value	
		LSMean	Std Error	LSMean	Std Error				
*Knee varus-valgus		11.58	1.42	10.24	1.34			0.0164	
*Knee rotation		25.13	1.72	22.52	1.76			0.0044	
*Pelvic tilt		3.36	0.12	3.58	0.15			0.0301	
*Hip rotation		11.97	0.899	14.66	0.93			<.0001	

Note. Bold letter with * indicates a statistical significance.

^{abc} means with a common superscripts in the same row are not significantly different (Tukey, $\alpha = 0.05$).

Figure 3. ROM at the pelvis and hip in the frontal plane.

4. Discussion and Conclusions

The linear trends for pelvic tilt demonstrate that the weight of the garment and carrying a load affected pelvic movement. ROM for pelvic tilt, which is closely related to a forward lean of the trunk, significantly increased with weight. Birrell and Haslam (2009) assert that forward lean of the trunk stabilizes the body's center of mass and helps to minimize energy expenditure during weight bearing. Nevertheless, forward inclination of the trunk that causes pelvic tilt has been suspected of possibly resulting in chronic lumbar pain (Smith et al., 2006). The current study also demonstrates that weight distribution influences ROM, as evidenced in pelvic tilt during walking. Our subjects exhibited a higher ROM for pelvic tilt for condition C7 (OTV + 18 kg carrying load on the back) compared to C6 (OTV + 9 kg carrying load on the front + 9 kg on the back symmetrically distributed). The C7 uneven weight distribution with loading only on the back may create the greatest forward lean of the trunk, while C6 uniform distribution around the torso was statistically the same as pelvic tilt for C1, C2, C3, C4, and C5. According to our results, balanced (right, left, front, and back) weight distribution placed around the torso (C6) may prevent forward lean of the trunk, thus alleviating the impact of weight on pelvic tilt in the sagittal plane. However, at 18 kg weight level in

loading only on the front side, there was no significant difference in ROM among three different weight distributions for C3, C4, and C5.

It is evident from the current study that ROM for pelvic rotation decreased appreciably as the overall weight load increased. LaFiandra, Wagenaar, Holt, and Obusek (2003) showed that an increase in upper body torque during weight bearing can lead to lower back injury. According to Birrell and Haslam (2009), decreased pelvic rotation while wearing a backpack minimized the application of a force at a point of rotation or at a perpendicular distance to a joint (torque) in the torso, as an intuitive attempt to dissipate the risk of low back pain and potential injury. Therefore, the reduced pelvic rotation is the human body's adaptive and protective response in order to minimize physical burden of the torso under weight-bearing conditions (Kinoshita, 1985).

However, the decreased pelvic rotation could have a negative impact on soldiers' walking efficiency according to the existing literature (Birrell & Haslam, 2009; Kinoshita, 1985). Reinhardt (2007) claimed that limited rotation of the pelvis decreases the efficiency of walking and running through limiting the leg's swing force to move the body forward. This induces a shorter stride length, which in turn necessitates higher stride frequency, to maintain the same walking speed under the load-carrying

Figure 4. ROM at the pelvis and hip in the sagittal plane.

Figure 5. ROM at the pelvis and hip in the transverse plane.

condition. The increased stride frequency resulting from limited pelvic rotation with shorter stride length can also cause possible early fatigue in an effort to maintain the same speed under military working conditions (Park et al., 2011).

Significant garment effects were found for ROM regarding hip adduction–abduction, hip flexion–extension, and hip rotation. Generally, ROM for the hip increased with weight, with the exception of the three 18 kg garment treatments (C3, C4, and C5). Post-hoc tests for hip flexion–extension verified a difference in ROM between (C1 and C7) and (C4 and C7). ROM for hip adduction–abduction and hip rotation displayed a decreasing trend up to the 18 kg garment treatments, and then increased for 27 kg (C6 and C7). These data trends may imply a compensational relationship between pelvis and hip movement. For instance, in the current study, ROM for pelvic rotation linearly decreased with weight. Hip rotation decreased as weight increased up to 18 kg. This may be because of the need for compensation for the decreased pelvic rotation as concluded in a previous study by LaFiandra et al. (2003). With subjects carrying backpacks that weighed 40% of body mass, those authors documented higher hip excursion, compensating for decreased pelvic rotation. Our observations concur with those of LaFiandra et al. (2003), suggesting the compensational relationship between pelvis and hip movement. Birrell and Haslam's (2009) study also disclosed a similar data pattern for hip rotation with an initial decreasing trend between zero to 8 kg, and a subsequent increase (between 8 kg, 16 kg, 24 kg, and 32 kg) at a controlled walking speed (1.5 m/s).

Prominent LR effects were documented for knee varus–valgus, knee rotation, pelvic tilt, and hip rotation. No interaction between garment and LR effects could be established. This may indicate a typical motion pattern of right-handed participants: greater ROM for knee varus–valgus and rotation on the right side than on the left; smaller ROM for pelvic tilt and hip rotation on the right side than on the left.

In sum, this study demonstrated how the weight of a body armor vest and the weight distribution of selected

loadings influenced lower body joint movement while walking at a slow pace. This study found that increased weight decreased lower limb mobility by restricting ROM for pelvic rotation. In particular, limited pelvic rotation may possibly decrease stride length and walking speed, which may require more frequent strides to maintain a constant walking speed (Kinoshita, 1985). This could increase soldiers' energy expenditure and cause early fatigue. Therefore, commanders need to consider the potential negative impact of walking with load carriage on soldiers' physical conditions during military tasks. Laing Treloar and Billing (2011) demonstrated that such negative impacts can be greater for female soldiers than males as evidenced by a larger decrease in sprint time with carrying load. In addition, Larsen et al. (2012) further reported that weight of body armor decreases soldiers' reaction time while performing high-intensity tasks as shown by longer times to complete given tasks such as shooting, crawling, and vaulting, as well as increased physiological strain.

Findings of this study also indicate that balanced weight distribution can help maintain an upright posture, which could minimize the risk of lower back pain resulting from an increased lean of the trunk—a known cause of chronic lumbar pain. This finding suggests that balanced weight distribution should be considered when designing military load-carriage systems and body armor, in addition to easy access to key items (ammunitions, grenades, walkie-talkies, etc.) for combat readiness. Therefore, wide hip belts, load lifters, or double pack structures should be examined to determine if they are helpful for creating more balanced weight distribution in the torso by shifting or sharing the weight of the loadings on the back to the pelvis or front torso. This may decrease the forward lean of the upper body and, as a result, help maintain an upright posture. Therefore, findings of this study suggest that an even weight distribution with easy access to key items should be considered for the design of body armor and load-carriage systems, which may help reduce soldiers' musculoskeletal injuries related to heavy weight bearing.

Results of this study provide useful health information not only for military personnel but also for anyone who

frequently wears a backpack to carry heavy loads. About 60% of youths experience at least one lower back pain incident by their teen years related to carrying a backpack and there are about 7000 emergency room visits every year resulting from load-carriage-related injuries (Arnsdorff & Carroll, 2009). The findings of this study will provide insight for designers of load-carriage systems, outdoor gear, and sporting goods. A balanced load distribution and possible reduction in weight should be considered as functional priorities to minimize potential negative impacts on lower limb mobility and musculoskeletal health.

5. Limitations and Future Studies

A crossover design with repeated measures was used to control the impact of sample order in this study. Upon completion of each test, a rest time was imposed, counteracting any potential sample order effect. This experimental design successfully blocked any effect of order of garment treatment on almost all dependent variables (11 ROMs), as ascertained by the insignificant effect of treatment order. However, a significant order effect was present for ROM pertaining to ankle rotation. Balancing for residual effects of treatment, recruiting at least two subjects for each sequence of treatments, combined with a longer rest time between treatments are recommended for future studies.

The current study focused on determination of changes in lower limb joint movement during walking trials conducted at a self-preferred pace to investigate a synergistic impact of weight and load distribution. This study did not include military footwear. Findings of this study suggest that an investigation of the impact of military footwear on soldiers' gait under heavy weight-bearing conditions is warranted. The small sample size in this study limited the generalization of the findings, although the current study addresses important issues and suggests further studies. This study did not include bilaterally unbalanced distribution on the back to avoid excessive complexity of experimental design with a small sample.

Future studies with more conditions of weight distributions and a greater number of participants may provide a deeper understanding of the biomechanic impact of weight distribution on soldiers' gait. This may have practical implications for the design of military load-carriage systems for improved soldier mobility. Similarly, investigation of the influence of size and fit of body armor on soldiers' mobility may also provide meaningful information to add to the current knowledge. This study did not investigate the relationship between joint angles and gait events during stance phase and swing phase in a gait cycle, yet further analysis would provide additional meaningful information. Future studies with tests of the same variables but at different speeds, and for longer distances, and with more subjects would enhance our understanding of the

effects of walking, carrying varying loads, and distribution of load on joint movement. Similarly, future studies should systematically investigate other movements commonly required for typical military performance, such as crawling and getting into and out of vehicles.

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