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BIOMECHANICAL, PHYSIOLOGICAL, AND AGILITY PERFORMANCE OF SOLDIERS CARRYING LOADS: A COMPARISON OF THE MODULAR LIGHTWEIGHT LOAD CARRYING EQUIPMENT AND A LIGHTNING PACKS, LLC, PROTOTYPE

by

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14. ABSTRACT
This report details a laboratory evaluation that compared a medium U.S. Army standard-issue Modular Lightweight Load-carrying Equipment (MOLLE) rucksack and a prototype energy-harvesting backpack from Lightning Packs (LP), LLC. A payload of 27.2 kg (60 lb) was placed in each pack. The total weights of the MOLLE and the LP were 30.1 kg (66.4 lb) and 34.6 kg (76.3 lb), respectively. The evaluation focused on comparing the two rucksack systems with regard to their effects on the biomechanical, physiological, and agility performance of Soldiers. The energy generation capabilities of the LP were also examined. Twelve male enlisted U.S. Army Soldiers (24.5 ± 3.9 years; 177.4 ± 5.8 cm; 84.3 ± 10.2 kg) participated in this evaluation. Gait kinetics, kinematics, and metabolic responses were measured during treadmill walking at a speed of 1.34 $m \cdot s^{-1}$ (3.0 $m \cdot h^{-1}$) on 0%, 5%, and -5% treadmill grades, as well as at 1.61 $m \cdot s^{-1}$ (3.6 $m \cdot h^{-1}$) at a 0% grade. Participants also completed a maximal effort agility drill in both pack configurations. The findings indicate that carrying the LP prototype is less metabolically efficient than carrying the MOLLE. The LP also affects the biomechanics of walking differently than the MOLLE, with significant differences in forward trunk lean angle, hip angle, and sagittal plane hip moments. In terms of energy harvesting and production during walking, the current weight penalty of carrying the LP prototype overrides the benefit of the energy harvesting capability of the prototype. Recommendations are made to improve performance of future LP systems.

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WALKING PROTOTYPES MOVEMENTS ARMY PERSONNEL PERFORMANCE(HUMAN)
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EXECUTIVE SUMMARY

Due to the unique power requirements of Soldiers in theatre, the military is investigating the use of passive energy harvesting technology that utilizes the kinetic energy of human movement to create electrical current. This report details a laboratory-based evaluation performed at the U.S. Army Natick Soldier Research, Development and Engineering Center that compared a medium U.S. Army standard-issue Modular Lightweight Load-carrying Equipment (MOLLE) rucksack and a prototype energy-harvesting backpack from Lightning Packs (LP), LLC (Wayne, PA). The evaluation focused on comparing the two rucksack systems with regard to their effects on the biomechanical, physiological, and agility performance of Soldiers. The energy generation capabilities of the LP were also examined.

The MOLLE backpack used in this evaluation was the standard-issue medium rucksack. This rucksack has a chest strap, padded shoulder straps, and a padded hip belt. The pack bag is mounted on a molded polymeric frame. The weight of all MOLLE rucksack components equals 2.9 kg (6.4 lb). The LP has a pack bag mounted on a load plate, which is attached to a rigid, external frame. The load plate is suspended from the frame by a spring system, allowing the plate and the pack bag attached to it to move vertically along the rigid frame, thereby decoupling the pack bag from the load-carrier's body movements (i.e., the load moves vertically, independently of the frame). As the springs recoil in opposition to the load-carrier's movements, the mechanical energy is converted to electrical energy, which is stored in a conformal-wearable battery located in the pack. Padded shoulder straps and a padded waist belt are attached to the frame. The weight of all components of the LP (not including the carried battery) is 7.4 kg (16.3 lb), which is 4.5 kg (9.9 lb) more than the weight of the MOLLE. Two identical sets of military items were assembled to constitute the payload placed in the MOLLE and the LP pack bags. The items totaled 27.2 kg (60.0 lb). Including all backpack components and the payload, the loaded MOLLE weighed 30.1 kg (66.4 lb) and the loaded LP weighed 34.6 kg (76.3 lb).

Twelve male enlisted U.S. Army Soldiers (24.5 ± 3.9 years; 177.4 ± 5.8 cm; 84.3 ± 10.2 kg) participated in this evaluation. All participants were infantry Soldiers with experience carrying rucksack loads. Gait kinetics, kinematics, and metabolic responses were measured during treadmill walking at a speed of 1.34 $m \cdot s^{-1}$ (3.0 $m \cdot h^{-1}$) on 0%, 5%, and -5% treadmill grades, as well as at 1.61 $m \cdot s^{-1}$ (3.6 $m \cdot h^{-1}$) at a 0% grade. Participants completed all treadmill testing twice: once in the standard MOLLE configuration, and once in the prototype LP configuration, for direct comparison between pack types. Participants also completed a maximal effort agility drill on a zigzag course in both pack configurations.

The findings from this study indicate that carrying the LP prototype is less metabolically efficient than carrying the MOLLE. The LP affects the biomechanics of walking differently than the MOLLE, with significant differences in forward trunk lean, hip angle, and sagittal plane hip moments, perhaps contributing to the higher metabolic cost. One element of the LP that may affect gait mechanics is the oscillation of the LP load on its frame and the resultant dynamic changes in load center of mass (COM) versus body COM. It is also possible that the location of the load relative to the load-carrier's back causes changes in posture and ground reaction forces that contribute to increased energy cost. In terms of energy harvesting and production during walking, the current weight penalty of carrying the LP prototype overrides the benefit of the energy harvesting capability of the LP prototype.

Recommendations to improve performance of future LP prototypes based on the findings from this evaluation are:

- Reduce the weight of the LP system
- Increase the device efficiency of the LP to reduce the cost of harvesting
- Reduce the depth of the LP frame design
- Design a study to test the effects of different oscillation frequencies on both power generation and gait mechanics. It is possible that tailoring the LP prototype oscillation frequency will isolate the effects of the LP on metabolic cost and walking biomechanics
- Recommendations for improved fit and comfort can be found in a report by Hennessy (2015), which summarizes findings from a questionnaire administered to the evaluation participants to obtain their opinions of the MOLLE and the LP

BIOMECHANICAL, PHYSIOLOGICAL, AND AGILITY PERFORMANCE OF SOLDIERS CARRYING LOADS: A COMPARISON OF THE MODULAR LIGHTWEIGHT LOAD CARRYING EQUIPMENT AND A LIGHTNING PACKS, LLC, PROTOTYPE

1. INTRODUCTION

This report details a laboratory-based evaluation conducted by the Biomechanics and Engineering Team at the U.S. Army Natick Soldier Research, Development and Engineering Center (NSRDEC) from September 2015 through October 2015. This evaluation was undertaken to compare a U.S. Army standard-issue Modular Lightweight Load-carrying Equipment (MOLLE) rucksack and a prototype rucksack from Lightning Packs, LLC (Wayne, PA) with regard to their effects on the biomechanical, physiological, and agility performance of Soldiers. The comfort of the Soldiers while carrying the packs was assessed, as well. In addition, questionnaire surveys were administered to the Soldiers who served as participants in this evaluation to obtain their opinions of the acceptability of the packs for carrying military loads (Hennessy, 2015). The Lightning Packs prototype, which is referred to as the “LP” in this report, was designed to generate energy during movement of the load carrier. The energy generation capabilities of the LP were also examined in this evaluation. The purpose of the effort was to acquire information on the acceptability of the LP for use as a military backpack and on the efficiency of the LP as an energy harvesting device. The information is necessary to guide decisions regarding development of future generations of military load-carrying equipment.

1.1 Background

Soldiers are often required to conduct foot marches while carrying heavy loads. A survey of the loads of U.S. infantry Soldiers in Afghanistan revealed that weights borne on some missions exceeded 45 kg (100 lb) and represented, on average, 57% of the body weight of the load carrier (Task Force Devil Combined Arms Assessment Team, 2003). There is a high metabolic cost to bearing heavy loads and these costs are likely to have a negative effect on efficient completion of foot marches and on the execution of high-intensity tactical operations (Pandolf, Givoni, & Goldman, 1977; Soule, Pandolf, & Goldman, 1978). Furthermore, vertical and anteroposterior ground reaction forces (GRFs) have been found to increase linearly with the load applied to the body (Birrell, Hooper, & Haslam, 2007; Polcyn et al., 2002). The increased GRFs are likely to demand greater muscle forces and to increase metabolic cost (Gottschall & Kram, 2003). High magnitudes of GRFs have been implicated, as well, in the occurrence of overuse injuries of the lower extremities (Knapik & Reynolds, 2012; Knapik, Reynolds, & Harman, 2004).

Ground troops are being provided with an increasing array of technologies that greatly enhance their operational effectiveness and survival. The devices, and the batteries needed to power them, add to the weight of the external loads that Soldiers must bear and, therefore, contribute to the negative effects associated with carrying heavy loads.

Power usage to operate these devices varies with the demands of the military mission, but it is known that the power usage within a standard, 9-man infantry squad is highest when engaging with the enemy and is lowest while conducting tactical movements (not in contact with the enemy). Tasks such as surveillance and scouting fall within these two extremes (Draper

Laboratory, 2014). As with power usage, the total duration of a squad's movements will vary depending on the mission. However, with a 72-h mission profile that has a concept of operations (CONOPS) including movement to contact, establishment of combat outposts, securing and holding an area (air assault), and cordoning and searching, there is an average of 12.6 h (±10 h) of tactical movement (Draper Laboratory, 2014).

During the same mission profile, a 9-man infantry squad expends an average 5270 W·h of energy under typical conditions (Draper Laboratory, 2014). This equates to roughly 586 W·h per Soldier. Assuming all squad members are carrying standard issue BB-2590/U batteries (180 W·h per battery), each Soldier is required to carry approximately 3.3 batteries (29.3 batteries per squad) to successfully complete the 72-h mission profile. The weight of a BB-2590/U battery is 1.41 kg (3.1 lb). If the batteries are evenly distributed across all squad members, each Soldier within the squad must carry at least 4.65 kg (10.3 lb) of battery weight.

Given the negative consequences of marching with heavy loads, military organizations are continually striving to reduce the weight of the loads that Soldiers must carry. One approach to address the load burden represented by batteries, while still providing Soldiers the benefits of the latest electronic technologies, is to use some form of passive energy harvesting that is compatible with Soldiers' activities during dismounted field operations. The LP from Lightning Packs, LLC, is an electricity generating backpack that is designed to carry loads and to generate electrical power during movement, such as walking and jogging. The LP uses the kinetic energy of human movement to generate power. A prototype of the LP was acquired by NSRDEC for this evaluation.

The LP consists of a pack bag mounted on an external frame. Shoulder straps and a waist belt are used to attach the frame to the user's body in the same manner as a traditional rucksack. However, the pack bag is free to move vertically along the rigid frame, thereby decoupling the pack load from the body. As load carriers walk, their center of mass (COM) naturally oscillates. Spring suspension of the LP allows the pack bag to oscillate in opposition to the vertical displacement of the user's COM. As the spring recoils, the mechanical energy is converted to electrical energy, which is then stored in an onboard battery. Spring stiffness and the weight and vertical displacement of the pack bag affect the amount of potential energy in the spring (Rome, Flynn, Goldman, & Yoo, 2005).

Rome et al. (2005) investigated the effectiveness of an early prototype of the LP design as an electricity generator. They tested six men carrying the LP system while walking at speeds of 1.11 $m \cdot s^{-1}$ (2.49 $mi \cdot h^{-1}$) to 1.78 $m \cdot s^{-1}$ (3.98 $mi \cdot h^{-1}$) on a treadmill set at 0% and at 10% grades. The LP itself weighed approximately 5.6 kg (12.3 lb) and loads of 20 kg (44.1 lb), 29 kg (63.9 lb), and 38 kg (83.8 lb) were placed in the pack bag. The men were tested for 7 min under each of the various speed, load, and grade combinations.

Rome et al. (2005) reported that the electrical power generated increased with speed and load weight. For example, at 0% grade and the lightest load (20 kg), mean electrical power output, in Watts (W), increased from about 0.5 W to 2.0 W, as speed increased from 1.11 $m \cdot s^{-1}$ (2.49 $mi \cdot h^{-1}$) to 1.78 $m \cdot s^{-1}$ (3.98 $mi \cdot h^{-1}$). At the 0% grade with the heaviest load (38 kg), mean power output increased from approximately 1.7 W at the lowest speed to about 7.4 W at the highest speed. Sample data on pack displacement indicated that walking with a 38-kg (83.8-lb) load at 1.56 $m \cdot s^{-1}$ (3.48 $mi \cdot h^{-1}$) resulted in movement of the pack bag relative to the frame of about 4.5 cm. Rome et al. (2005) also reported that mean power output for a given speed and load weight during walking up the 10% grade was equal to or greater than that when walking on the 0% grade.

Rome et al. (2005) measured the rate of oxygen consumption ($\dot{V}O_2$) and carbon dioxide production as the men walked on the treadmill. For this analysis, data were obtained with the pack bag free to oscillate independent of the frame (i.e., unlocked configuration), and also with the pack bag locked in position (i.e., locked configuration), unable to oscillate. Rome et al. (2005) reported the finding that, compared with the locked configuration, the unlocked configuration resulted in reduction of the peak force exerted by the load on the load carrier (as measured at the pack frame via load cells). Rome et al. (2005) also found that, although $\dot{V}O_2$ was higher with the LP in the unlocked configuration, the difference between the unlocked and the locked configurations was small, 19.1 W. They ascribed these findings to differences in the characteristics of walking gait or loading regimen between the unlocked and the locked configurations that affected the amount of positive work performed during the double support phase of the gait cycle, the phase of the gait cycle when both feet are in contact with the ground.

To quantify the efficiency of biomechanical energy harvesting devices, such as the LP, Donelan et al. (2008) proposed a dimensionless quantity referred to as the "cost of harvesting" (COH). The COH (Equation 1) is defined as the additional metabolic power (W) required to generate 1 W of electrical power.

$$COH = \frac{\Delta\, metabolic\ power}{\Delta\, electrical\ power} = \frac{1}{device\ efficiency \times muscle\ efficiency} \qquad (1)$$

where, Δ refers to the difference between walking while harvesting energy and walking while carrying the device, but without harvesting energy.

For conventional power generation, Donelan et al. (2008) stated that the COH is related to the efficiency with which the energy harvesting device converts mechanical work to electricity and muscles convert chemical energy to positive work (Equation 1). A lower COH value indicates a lower cost for harvesting electrical power. A higher COH indicates a higher cost for harvesting electrical power. A lower COH is considered more desirable. Donelan et al. (2008) reported a device efficiency of 31% for the backpack tested by Rome et al. (2005). Muscle peak efficiency has been reported to be about 25% (Donelan et al., 2008). This yields an expected COH of 12.9. Donelan et al. (2008) reported an actual COH for the early LP prototype of 4.8 ± 3.0 (mean ± *SD*). This value is less than 40% of the expected value and, thus, reflects favorably on the LP as an energy generating device.

The results reported by Donelan et al. (2008) and Rome et al. (2005) indicate that the LP has promise as an energy harvesting device. However, data were lacking on performance of the LP as a load-carrying device for Soldiers. Therefore, O'Donovan, Batty, Gregorczyk, and Bensel (2015) conducted a small-scale, pilot evaluation at NSRDEC on three individuals carrying a loaded LP prototype and contrasted that with parallel data on the same individuals carrying a loaded standard-issue Army rucksack. The limited evaluation included more extensive biomechanical and metabolic measurements than those made by Rome et al. (2005). A particular focus of the investigators was to expand on the data that Rome et al. (2005) had collected regarding the forces to which the load carrier is exposed when walking and jogging with the LP.

O'Donovan et al. (2015) recorded kinetic, kinematic, and metabolic data, but did not collect data on electrical power generation with the LP. In addition to the LP prototype, a second backpack prototype developed by Lightning Packs, LLC, was included in the evaluation (Rome, Flynn, & Yoo, 2006), along with a standard Army MOLLE large rucksack. The MOLLE large rucksack is a pack bag with a volume of 0.065 m^3 (4000 $in.^3$) mounted on a frame. When unloaded, the MOLLE backpack weighs 3.7 kg (8.2 lb), inclusive of all components. Both prototype backpacks from Lightning Packs tested by O'Donovan et al. (2015) weighed about 4 kg (9 lb) more than the MOLLE. For the evaluation, O'Donovan et al. (2015) placed military gear in the pack bags to achieve a total weight of 27 kg (60 lb), including all components of the backpacks themselves. Thus, the payload weight of military gear put in the MOLLE pack was 23 kg (51 lb) and the payloads for the two prototype packs were 19 kg (42 lb).

Two of the three individuals who participated in the O'Donovan et al. (2015) evaluation, one man and one woman, were U.S. Army enlisted personnel with some limited experience conducting foot marches with loads, but no experience with packs from Lightning Packs, LLC. The third individual was a male civilian who had been a U.S. Marine Corps sergeant. He was very experienced in the carrying of military loads and also had extensive experience carrying the packs from Lightning Packs. For testing, the participants carried out 6-min trials with each pack while walking on a treadmill set at 0% grade and a speed of 1.34 $m \cdot s^{-1}$ (3 $mi \cdot h^{-1}$). Similarly, during a subsequent session, participants had 6-min trials during which they jogged with each pack at a self-selected pace. The individuals selected jogging speeds of 2.10 $m \cdot s^{-1}$ (4.5 $mi \cdot h^{-1}$) to 2.68 $m \cdot s^{-1}$ (6.0 $mi \cdot h^{-1}$). A shirt, trousers, and combat boots were worn during testing. Participants were not outfitted in other clothing and personal protective equipment that dismounted Soldiers typically wear, such as a helmet, an armor vest, or a fighting load.

Because of the small number of participants, O'Donovan et al. (2015) did not subject the data they collected to statistical treatment. They did obtain summary statistics for each individual participant and examined the data for consistency of the relationships among pack conditions across the participants. Of particular interest to the investigators were any differences in GRF results between the LP and the MOLLE. In this regard, O'Donovan et al. (2015) found that peak loading responses at heel strike during walking were not consistently higher nor lower with the LP than with the MOLLE. However, vertical forces at mid-stance during walking were higher with the LP for all three participants. Further, vertical forces at push-off during walking were lower with the LP than with the MOLLE for two of the three participants. For the anteroposterior GRF variables, there was a tendency among the participants for peak propulsive force during walking to be lower with the LP than with the MOLLE. In terms of joint moments during walking, a consistent trend for all three participants was that peak knee flexion and extension moments were slightly lower with the LP than with the MOLLE. With regard to jogging results for the GRFs and other force-related variables, O'Donovan et al. (2015) reported that the LP was not more effective in reducing forces on the body, knee moments, and loading rates compared with the MOLLE.

In examining spatiotemporal variables for walking, such as stride length and double support duration, O'Donovan et al. (2015) reported that there were no consistent differences between the LP and the MOLLE. This was also the case for the spatiotemporal variables recorded during jogging. The $\dot{V}O_2$ measures, as well, did not reveal consistent differences between the LP and the MOLLE during walking or jogging.

As an adjunct to the evaluation conducted by O'Donovan et al. (2015), Sniezek (2014) prepared a questionnaire seeking participants' opinions on the comfort, stability, and related characteristics of the MOLLE and the backpack prototypes from Lightning Packs, LLC. The questionnaire was administered to the two Army enlistees as they completed trials of walking and jogging in the backpacks.

Sniezek (2014) reported that both enlisted personnel indicated a preference for the LP, rather than the MOLLE. They maintained that the weight of the load during walking was not as well distributed with the MOLLE as it was when the LP was worn. In particular, the enlistees indicated that the load seemed to be located low on the back with the MOLLE, causing pain and imbalance (Sniezek, 2014).

Considering the overall results, O'Donovan et al. (2015) concluded that the LP did not place a greater burden on the load carrier than the MOLLE did during walking, but that use of the LP pack during jogging activities was questionable. They recommended that a study of the LP be undertaken with a larger number of participants, preferably Soldiers with experience carrying military loads while engaging in foot marches. O'Donovan et al. (2015) also recommended that participants in future testing be outfitted in the clothing and protective equipment that Soldiers typically wear during field exercises and foot marches. A larger scale evaluation of the LP was subsequently undertaken by NSRDEC. It is the subject of this report.

1.2 Current Study

The LP prototype used in this evaluation included hardware and design updates, but functioned in a similar manner to the prototype tested by O'Donovan et al. (2015). The weight of the LP prototype version evaluated here, including the frame and all other components of the backpack itself, was 7.4 kg (16.3 lb), which was 0.7 kg (1.5 lb) less than the weight of the earlier LP prototype. A standard-issue Army rucksack was again included in the testing. Instead of the MOLLE large rucksack, which O'Donovan et al. (2015) used, the MOLLE medium rucksack was used here. The weight of the unloaded MOLLE medium rucksack, including its frame and all other components, is 2.9 kg (6.4 lb). Thus, without a load in the pack bags, the LP prototype tested here was 4.5 kg (9.9 lb) heavier than the medium rucksack.

In the previous testing done by O'Donovan et al. (2015), a lighter payload [19 kg (42 lb)] was placed in the LP pack bag than was placed in the MOLLE [23 kg (51 lb)] to achieve equal total weights for both loaded backpacks of 27 kg (60 lb). For the evaluation described here, the option of reducing the payload carried in the LP pack bag by 4.5 kg (9.9 lb) to again equalize the weights of the loaded LP and the loaded MOLLE was considered. However, Soldiers conducting missions that entail carrying backpacks do not have the flexibility of omitting items to reduce payload weights. Therefore, it was determined that, for this evaluation, one operationally relevant payload of military items weighing 27.2 kg (60 lb) would be placed in the pack bags of both the LP and the MOLLE. With this payload, the weight of the loaded LP was 34.6 kg (76.3 lb) and the weight of the loaded MOLLE was 30.1 kg (66.4 lb).

Participants in this evaluation were outfitted in clothing and equipment that Soldiers use during dismounted operations, and they wore these items throughout testing. The items included a helmet, an armor vest with ballistic protective plates, and a fighting load carrier. Participants also carried a mock M16 rifle throughout testing. The weight of these items, plus a shirt, trousers, and combat boots, was approximately 22.9 kg (50.5 lb). In the earlier testing by O'Donovan et al. (2015), participants wore only a shirt, trousers, and combat boots. Therefore, the current evaluation entailed not only bearing heavier loaded rucksacks, but also wearing and carrying items typically used during military field operations.

As was done during the previous evaluation conducted by O'Donovan et al. (2015), participants' opinions regarding the MOLLE and the LP packs were solicited using questionnaire surveys administered over the testing comprising the present evaluation. The results of the surveys are presented in a report by Hennessy (2015).

Hennessy (2015) posed a number of survey questions that entailed rating on 7-point Likert-type scales characteristics of each pack, such as pressure and pain on the body, load balance and stability, and pack comfort. Hennessy (2015) found that the ratings indicated participants experienced more pressure and pain with the LP than with the MOLLE. Load balance and stability were also rated less positively for the LP than for the MOLLE and the comfort of LP was rated lower.

On a number of survey questions, Hennessy (2015) requested that participants select which of the two packs they preferred for particular attributes. The MOLLE was generally preferred to the LP, particularly for the attributes of comfort, weight distribution, and compatibility with military missions. Comments made by participants indicated that some individuals experienced a rearward pull of the load when using the LP, which they attributed to the load being located low on their backs and being displaced posteriorly (Hennessy, 2015). Other comments addressed the experiencing of a "bouncing," or oscillation, of the LP on the back, which resulted in reports of pack instability.

In the current evaluation, participants were tested in the MOLLE and the LP packs as they walked on a treadmill at different grades and speeds. Biomechanical data, including GRFs and other force-related variables, were recorded in this assessment to inform NSRDEC as to whether the reduction in force exerted on the load carrier by the LP, which was reported by Rome et al. (2005) in the testing of an earlier LP prototype, translates to reduced peak GRFs during walking in the current LP prototype design. The GRF data acquired during walking were complemented by spatiotemporal, kinematic, metabolic, and subjective physical exertion measures to further investigate the effects of the LP when compared to a standard Army backpack.

In addition to the walking activity, the participants in this evaluation performed a maximal effort agility run. Cones were set up to delineate a zigzag course and participants were instructed to complete the course as quickly as possible while carrying the LP and while carrying the MOLLE. Course completion time and kinematic data were recorded for this activity.

The purpose of this evaluation was two-fold: (1) Compare the LP and the standard-issue MOLLE on measures of Soldier biomechanics, metabolics, agility performance, and perceived exertion; and (2) Determine how effectively the LP system harvests power during walking at different speeds and grades with a militarily relevant load.

2. METHODS

The evaluation presented in this report was conducted at NSRDEC, Natick, MA. It was performed in accordance with the NSRDEC Assurance for the Protection of Human Subjects (DoDA20124, dated 1 April 2008). The NSRDEC Human Subject Research Determination Panel determined that this activity did not meet the regulatory definition of human subject research, as defined by the Federal Policy for the Protection of Human Subjects, U.S. Department of Defense, 32 Code of Federal Regulations Part 219.102 (Definitions). Institutional Authority Approval was obtained before data collection took place.

2.1 Participants

Twelve U.S. Army enlisted men volunteered for the evaluation. The men were from the Maneuver Battle Lab, Ft. Benning, GA, and were assigned to NSRDEC for the duration of the evaluation. Prior to volunteering, the Soldiers were informed of the purpose, the nature of the test conditions, the risks associated with the testing, all procedures affecting a volunteer's well-being, and a volunteer's right to discontinue participation at any time without penalty. Individuals who had experienced any lower extremity injuries that would affect normal gait patterns or inhibit ability to complete the required testing were excluded from participation.

Demographic information on the men is presented in Table 1. All participants were infantrymen (Military Occupational Specialty 11B) with experience carrying rucksack loads. The men were queried with regard to the frequency with which they conducted field operations that involved load carriage in their present assignments. Eight men reported that they carried rucksack loads at least once per month and four of these men indicated that they conducted operations with loads at least once per week. The remaining four men indicated that they carried rucksack loads once per month or less frequently in their current assignments. The mean stature and weight of the participants (Table 1) were approximately equal to the 60th and the 50th percentiles, respectively, calculated from the measurements for 4082 men acquired in the most recent anthropometric survey of U.S. Army personnel (Gordon et al., 2014). Thus, the participants were, on average, somewhat taller and about the same weight compared with the median measurements for the large sample of Army men.

Table 1: *Demographics of participants (N = 12).*

Measure	Mean	*SD*
Time in service (years)	3.97	2.68
Age (years)	24.50	3.92
Stature (cm)	177.44	5.84
Weight (kg)	84.28	10.15

2.2 Pack Conditions

The MOLLE backpack used in this evaluation was the standard-issue medium rucksack (Figure 1). This rucksack has a chest strap, padded shoulder straps and a padded hip belt. The pack bag has a volume of 0.049 m^3 (3000 in^3) and is mounted on a molded polymeric frame. The weight of all MOLLE rucksack components equals 2.9 kg (6.4 lb).

The LP has a pack bag mounted on a load plate, which is attached to a rigid, external frame (Figure 1). The pack bag has a volume of 0.049 m^3 (3000 in^3). The load plate is suspended from the frame by a spring system, allowing the plate and the pack bag attached to it to move vertically along the rigid frame, thereby decoupling the pack bag from the load-carrier's body movements (i.e., the load moves vertically, independently of the frame). As the springs recoil in opposition to the load-carrier's movements, the mechanical energy is converted to electrical energy, which is stored in a conformal-wearable battery (CWB-150) located in the pack. Padded shoulder straps and a padded waist belt are attached to the frame. The weight of all components of the LP (not including the carried battery) is 7.4 kg (16.3 lb).

Figure 1: *(A) MOLLE medium rucksack. (B) Schematic of the load plate and frame for the prototype electricity generating pack from Lightning Packs, LLC. (C) LP medium rucksack.*

In the energy harvesting mode of the LP, the pack bag is free to oscillate independent of the frame. However, the pack bag can also be locked in position so that it does not move relative to the frame. Throughout this evaluation, the LP was tested in the unlocked configuration, with the pack bag free to move vertically along the frame.

Two identical sets of military items were assembled to constitute the payload placed in the MOLLE and the LP pack bags. The items totaled 27.2 kg (60.0 lb) and consisted of simulated ammunition, clothing, and communication equipment. The payload weight was selected to reflect the weight of an operationally relevant military load. Payloads of about this weight are carried within an infantry squad by radio telephone operators and 60-mm mortar gunners and assistant gunners (Task Force Devil Combined Arms Assessment Team, 2003).

Throughout testing, participants wore a basic outfit consisting of torso clothing, combat boots, an Army Combat Helmet (ACH), a 3rd Generation Improved Outer Tactical Vest (IOTV), and a Tactical Assault Panel (TAP). The Enhanced Small Arms Protective Inserts (ESAPI) were placed in the front and back pockets of the IOTV and the Enhanced Side Ballistic Inserts (ESBI) were placed in the side pockets. The yoke was also attached to the IOTV. The TAP contained weighted simulated grenades and ammunition. In addition, participants carried a mock M16 rifle throughout testing. While walking on the treadmill, the participants wore tight-fitting, spandex shirts and shorts supplied by the investigators as their torso clothing. During the agility run, the torso clothing consisted of the participants' own Army Combat Uniform (ACU) shirts and trousers. The weight of the clothing, protective equipment, and the rifle was approximately 22.9 kg (50.5 lb).

Table 2 shows a list of the weights of the components comprising the pack conditions. The difference in weights between the two pack conditions is attributable solely to a difference in the weights of the two backpack systems themselves. The unloaded MOLLE weighs 4.5 kg (9.9 lb) less than the unloaded LP.

Table 2: *Weights (in kg) of components of pack conditions.*

Pack Type	Unloaded Pack	Pack Payload	Loaded Pack	External Load on Body[a]
MOLLE	2.9	27.2	30.1	53.0
LP	7.4	27.2	34.6	57.5

[a]External load weight is the weight of all items worn or carried by the participant (i.e., skin-out weight).

2.3 Testing Equipment & Procedures

2.3.1 Overview

Participants attended two orientation sessions followed by four testing sessions. The orientation served to familiarize the participants with the activities that they would perform during the evaluation. The first two testing sessions involved treadmill walking and the last two involved execution of agility runs. The testing activities, as well as the principal measures taken in conjunction with the testing, were:

- Biomechanical responses and physiological energy usage during treadmill walking at a speed of 1.34 $m \cdot s^{-1}$ (3.0 $mi \cdot h^{-1}$) for 6 min on 0%, 5%, and -5% grades

- Biomechanical responses and physiological energy usage during treadmill walking at a speed of 1.61 m·s^{-1} (3.6 mi·h^{-1}) for 6 min on a 0% grade
- Power outputs and displacement of the LP during treadmill walking
- Completion time, angular velocities, and angular accelerations during a maximal effort agility run on a zigzag course
- Subjective ratings of exertion upon completion of treadmill walking and agility runs

Each participant completed all testing in the two pack conditions. Prior to the start of testing, orders in which the participants were to be exposed to the conditions were established to avoid confounding and bias in the data.

2.3.2 Orientation

During the first of the two orientation sessions, body dimension measurements were made on the participants (Hotzman et al., 2011) and the participants were fitted for the clothing and equipment to be used during testing, including the MOLLE and the LP packs. Safety procedures were explained by the investigators and participants' questions on testing methods were addressed. Participants also were familiarized with walking on the treadmill. During treadmill familiarization, participants walked at 1.34 m·s^{-1} (3.0 mi·h^{-1}) on grades set at 0%, 5%, and -5% while carrying each of the two pack conditions. They also walked at 1.61 m·s^{-1} (3.6 mi·h^{-1}) on a 0% grade with each of the packs. Therefore, participants had exposure to the load, speed, and grade conditions under which they were subsequently tested. During the second orientation session, which was conducted on a separate day from the first orientation session, the agility run was introduced and participants practiced executing the zigzag route while wearing each of the pack conditions. By the end of each orientation session, a participant had worn each of the two packs for about 1 h.

2.3.3 Treadmill Walking Testing

The testing that entailed treadmill walking was conducted at NSRDEC's Center for Military Biomechanics Research. Data were acquired from each participant under the two pack conditions. A participant was tested in one pack at the first session and in the other pack at the second session. The sessions were separated by at least two days to allow for full recovery between sessions.

2.3.3.1 Equipment and Measurements

Kinetics

An integrated force plate treadmill, fabricated by AMTI (Watertown, MA), was used for the treadmill walking testing. This treadmill is comprised of two synchronized side-by-side belts located on a single platform. The treadmill belts sit close together, with a gap of less than 10 mm. The motors for the treadmill belts are synchronized and feedback controlled so that, if the speed of one belt changes, the other belt maintains an identical speed. The treadmill can attain speeds of up to 5.28 m·s^{-1} (11.8 mi·h^{-1}) and can be set at grades of ± 25%. Each belt is mounted over a force plate, which is capable of measuring GRFs in three planes. Each force plate in the treadmill provides six continuous voltage output signals corresponding to forces and torques in three orthogonal directions (x, y, z). For this study, the voltage outputs of the force plates were sampled at the rate of 1200 Hz, filtered with a low-pass Butterworth filter (cut-off frequency of 10 Hz), and converted to physical units, Newtons (N), using manufacturer-supplied calibration factors.

A number of kinetic variables were derived from the participants' force-time histories outputted from the force plate treadmill during walking. In analyzing locomotion, GRF is generally decomposed into three orthogonal components. The directions of the components are at right angles to each other: vertical (Z-axis), anteroposterior (X-axis), and mediolateral (Y-axis). By convention (Nigg, 1986), the vertical force is positive; the positive direction is upward, indicating that the force is exerted by the ground on the foot. The anteroposterior component is commonly referred to as the braking-propulsive component. It is the horizontal force exerted by the ground on the foot in the direction opposite locomotion (braking) or in the same direction as locomotion (propulsive). By convention (Nigg, 1986), braking force is expressed as a negative number and propulsive force as a positive number. The mediolateral component is horizontal force exerted by the ground on the foot toward or away from the midline of the body.

Figure 2 contains an illustration of the force plate axes designations and examples of GRF patterns during walking. The patterns of force-time histories of walking strides differ among individuals. However, typical patterns associated with walking are graphed in Figure 2 for each component of the GRF. The abscissa in the graphs is percentage of stance time. Stance time is the elapsed time from initial contact of one foot with the ground until that same foot leaves the ground. The vertical GRF component for walking shows two peaks, as illustrated in Figure 2. The first peak force (the load response peak force) occurs early in the stride cycle, at initial contact of the foot with the ground, and the second peak force (the thrust peak force) occurs later in the stride cycle, when the foot is pushing off from the ground. The mid-stance period of the gait cycle occurs between the first and the second peak vertical forces. The anteroposterior component also tends to have two peaks, a braking peak during the initial phase of ground contact and a propulsive peak during the later phase (Figure 2).

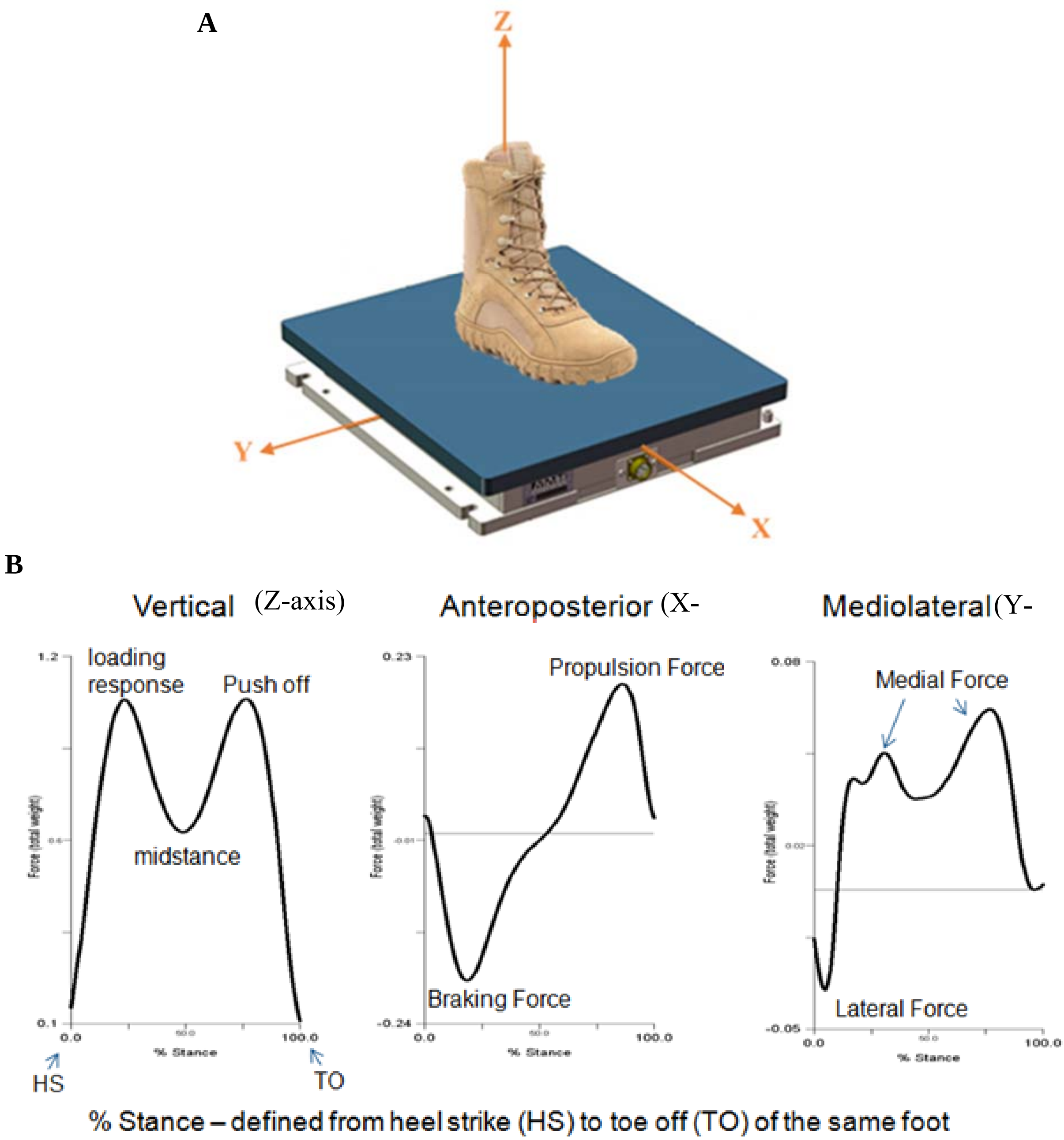


Figure 2: *(A) Illustration of force plate axes designations. (B) Examples of GRF during walking.*

In addition to the GRF components, hip, knee, and ankle joint moments in the sagittal plane were analyzed. A net joint moment is the minimum moment required at a joint to obtain the observed kinematics, or body movement. Joint moments describe the overall mechanical demand placed on the muscles due to movement of the joint. Higher joint moments are generally considered unfavorable due to increased demand on the musculoskeletal system and the increased potential for injury (Knapik & Reynolds, 2012; Knapik et al., 2004).

Loading rate, calculated from the slope of the vertical GRF curve (Figure 2) during initial impact of the foot with the ground, was analyzed as well. Loading rate in this context refers to the speed with which forces are applied to the lower extremities as a result of the external load applied to the body and the activity being performed. High loading rates have been associated with increased injury risk, including stress fractures in Soldiers (Knapik & Reynolds, 2012; Knapik et al., 2004).

Kinematics

As the participants walked on the treadmill, three-dimensional (3D) body motion was recorded by Oqus cameras (Qualisys AB, Gothenburg, Sweden). Retro-reflective markers, 12 mm in diameter, were placed at selected anatomical locations on the participant's skin and clothing to expedite processing of the recorded images. Clusters of four markers, joined by a rigid plastic plate, were also secured on seven body segments (bilateral thigh, bilateral shank, bilateral foot, and torso). The thigh clusters were placed over the spandex shorts, the shank clusters were placed on the anterior of the shank, the foot clusters were placed on the heel portion of the combat boot, and the torso cluster was placed at chest level on the front of the IOTV. When the LP was used, markers were also placed on the pack bag and on the frame.

Twelve Oqus cameras, operating at 120 Hz and focused on the area of the treadmill, were used to capture treadmill walking movements. The cameras were positioned on each side and anterior and posterior to the viewing area. This allowed the kinematics of the whole body to be defined in 3D space with 6 degrees of freedom for each body segment. The outputs of the cameras and the force plates were time-synchronized.

The recorded images were processed using dedicated hardware and software (Qualisys AB, Gothenburg, Sweden) to produce files containing time histories of the 3D coordinates of each reflective marker. Marker trajectories were low-pass filtered with a fourth order Butterworth filter at a cut-off frequency of 6 Hz. The Visual3D™ software program (C-motion, Inc., Germantown, MD) was used to process the data files and to obtain a number of kinematic variables describing the participant's posture and the spatial and temporal characteristics of the participant's gait.

Body angles that were calculated to describe the participant's posture were sagittal plane hip, knee, ankle, and trunk angles (Figure 3). The hip angle describes the angle formed by the thigh and the trunk. Higher hip angle values indicate greater flexion. The knee angle is formed by the thigh and the shank. Higher values denote greater flexion at the knee. The ankle angle is formed by the shank and the foot. Positive values indicate foot dorsiflexion and negative values indicate plantar flexion. Trunk angle is a measure of forward lean of the torso. This angle was calculated with regard to the vertical. Higher trunk angle values denote greater forward lean and lower values indicate a more upright posture.

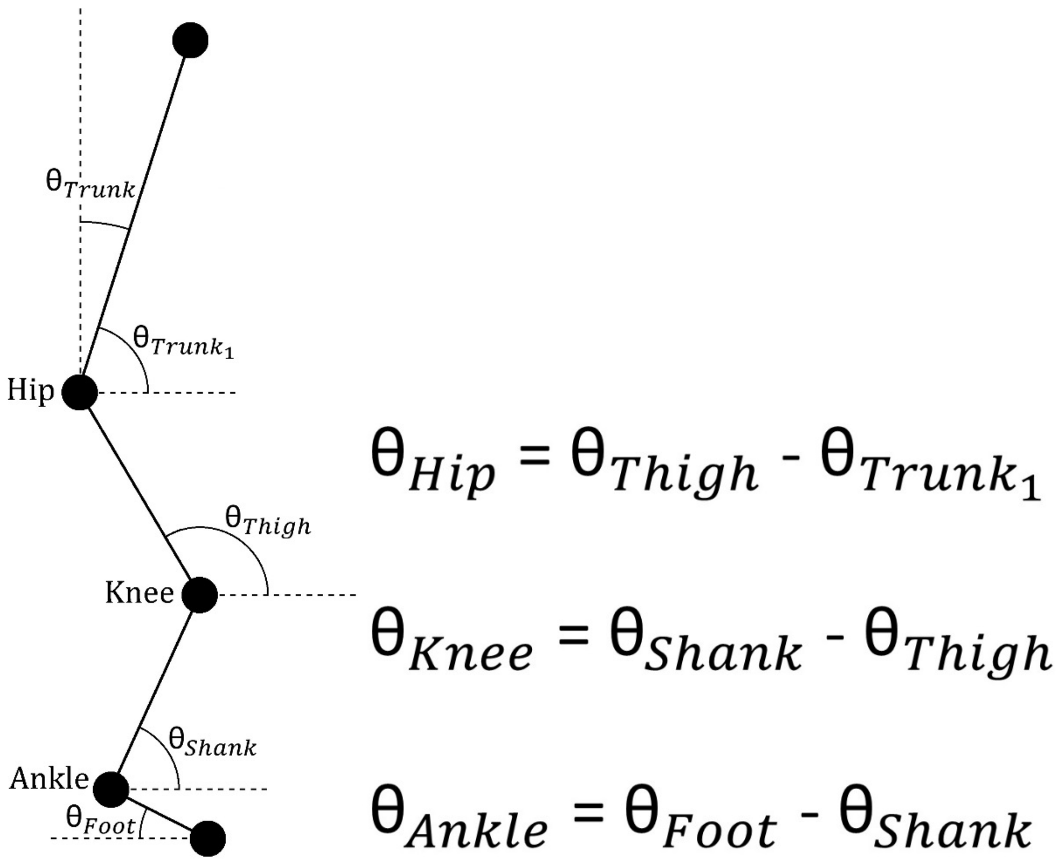


Figure 3: *Schematic of joint angle definitions for kinematic results.*

Immediately prior to each walking trial, the participant stood upright in a stationary position on the treadmill while the cameras were activated for 5 s. The body angles illustrated in Figure 3 were obtained from the kinematic data captured during this calibration period. The kinematic data subsequently captured during treadmill walking were treated in the same manner (Figure 3) to obtain body angles for walking. Each of the body angles calculated from the walking data was adjusted by subtracting it from the same body angle obtained during the calibration period. Body angle variables obtained for each walking stride from the data set of adjusted body angles were maximum angle, minimum angle, and range of motion (ROM), or the difference between the maximum and the minimum angles.

The spatiotemporal gait variables that were calculated from the body motion data are listed and defined in Table 3. As indicated in the table, stance duration, swing duration, and double support duration for a stride were expressed as percentages of time to complete the stride.

Table 3: *Definitions of spatiotemporal variables.*

Variable	Definition
Stride length (m)	The linear distance from the point of heel strike of one foot with the ground to the point of the next heel contact of the same foot with the ground.
Stride width (m)	The medial-lateral distance between the right and the left heels as measured at the time of heel strike of each foot.
Stride time (s)	The time from heel strike of one foot with the ground to the time of the next heel strike of the same foot. Stride time is also commonly referred to as cycle time.
Stance duration (% stride time)	The time from heel strike of one foot with the ground to the time of toe-off of the same foot from the ground. It is expressed here as a percentage of stride time.
Swing duration (% stride time)	The time from toe-off of one foot from the ground until heel strike of the same foot with the ground. It is expressed here as a percentage of stride time.
Double support duration (% stride time)	The time that both feet are in contact with the ground. It is also referred to as double stance. Double support duration is expressed here as a percentage of stride time.

Metabolics

Metabolic measurements and heart rate (HR) were recorded during treadmill walking trials using a Quark CPET (COSMED, Rome, Italy) metabolic measurement system. The $\dot{V}O_2$ and the HR were measured on a breath-by-breath basis. The $\dot{V}O_2$ measurements were outputted as absolute values ($ml\cdot min^{-1}$) and the HR data were in $beats\cdot min^{-1}$. Each day, prior to the start of testing, the metabolic measurement system was calibrated to known gas concentrations following manufacturer-supplied instructions.

LP Measurements

When the LP was worn during treadmill walking, retro-reflective markers were placed on the pack bag and on the frame. Movements of the pack and the frame were captured by the Oqus cameras simultaneously with the recording of the body motions. Displacement of the pack relative to the frame was calculated from the recorded images. Higher values indicate a greater distance of the pack from the top of the frame (i.e., the pack is lower down on the frame). The maximum and minimum displacements were obtained, as was ROM. Power output data were also collected during treadmill walking at a sampling rate of 100 Hz from the generator on the LP. These data were processed using dedicated hardware and software (*E*-Soldier, Natick, MA) to produce files containing time-histories of the current and the voltage outputs of the pack.

Subjective Assessments

Toward the end of each trial of treadmill walking, the 15-category Rating of Perceived Exertion (RPE) scale, devised by Borg (1970, 1982), was administered to assess the perceived exertion associated with the walking (Appendix A). The RPE is widely used in clinical diagnostics, athletic training, and epidemiological evaluations of exercise intensity (Noble, 1982; Pandolf, 1982).

A human factors questionnaire was administered upon completion of a walking trial. Participants' opinions regarding the pack condition they had just tested were solicited, including their perceptions of discomfort and acceptability of the backpack. The results are presented in a report by Hennessy (2015).

2.3.3.2 Procedure

Whether the MOLLE or the LP backpack was worn at the first or the second session of the treadmill walking testing was randomly determined for each participant. The activities carried out at each session were identical. A session was comprised of four walking trials, each of which was approximately 6 min in duration and was followed by a rest break of 10 min. The first three trials were conducted at a speed of 1.34 $m \cdot s^{-1}$ (3.0 $mi \cdot h^{-1}$) and the treadmill was set to a different grade for each of these trials. The order in which the three grades (0%, 5%, -5%) were tested was randomly determined for each participant. The fourth and last trial of a session was conducted with the treadmill set at a speed of 1.61 $m \cdot s^{-1}$ (3.6 $mi \cdot h^{-1}$) and a 0% grade.

Two min of resting metabolic data, taken during both seated resting and standing resting, were collected prior to the start of each trial. In addition, test participants stood upright on the treadmill in a stationary position while 5 s of kinematic data were recorded for calibration purposes. Participants were instructed to hold the weapon with both hands in front of the body (i.e., in the low-ready position) and to walk in their normal manner throughout the 6-min treadmill walking trial. Data were not collected during the first 3 min of the trial to allow the test participant to reach a physiological steady-state. At the 3-min mark in the trial, data collection began. Force plate and motion capture camera outputs were recorded simultaneously for 30 s. Breath-by-breath metabolic data and HR were collected for the last 2 min of each trial. When the participant was testing the LP prototype, 2 min of power output data were collected simultaneously with the metabolic data. The RPE (Appendix A) was administered immediately at the end of the trial. After the treadmill was stopped, the human factors questionnaire was administered (Hennessy, 2015). This activity was followed by a 10-min rest break before the next trial began.

In preparation for statistical analysis of the time-synchronized outputs of the force plates and motion capture cameras, 10 successive strides (five measured from left heel strike to the next left heel strike; five measured from right heel strike to the next right heel strike) were selected from each participant's data. Each of the 10 strides was processed using the Visual3D software program to obtain the values of the kinetic and the kinematic gait variables. A mean for each variable, which was calculated over the 10 strides, served as a participant's raw data for the statistical analysis. The GRF data were expressed as the measured force (N) normalized to the participant's body weight ($N \cdot kg^{-1}$) and normalized to the participant's total weight ($N \cdot kg^{-1}$). Total weight was calculated as body weight plus the weight of all items worn or carried on the body.

The metabolic and HR data recorded were also processed for analysis. The breath-by-breath $\dot{V}O_2$ measurements and the HR measurements were averaged over the 2-min recording period. For analysis purposes, $\dot{V}O_2$ was scaled to the participant's body weight ($ml \cdot kg^{-1} \cdot min^{-1}$) and to the total of the participant's body weight plus the weight of all items worn or carried on the body ($ml \cdot kg^{-1} \cdot min^{-1}$).

2.3.4 Maximal Effort Agility Run Testing

Agility testing was conducted outdoors on flat, grassy terrain at NSRDEC. Participants completed two agility sessions. Both sessions were conducted on the same day. Participants had approximately 1 h of rest between the two sessions. Participants completed the first session in one of the two pack conditions and switched to the remaining pack condition for the second session. The order in which a participant tested the packs was determined randomly. During each run, participants carried the mock M16 rifle in the low-ready position.

2.3.4.1 Equipment and Measurements

Traffic cones were used to delineate a zigzag course for the agility run (Figure 4). An inertial measurement unit (IMU; APDM Wearable Technologies, Portland, OR) was affixed to the participant's sacrum with athletic tape. The IMU was used to collect timing data and kinematic data (angular velocity and acceleration). Custom algorithms developed by the University of Michigan (Ann Arbor, MI) processed the raw kinematic data to output various performance metrics, including time to complete the course, speeds, angular velocities, normal and tangential accelerations, and pelvic tilt at the turns.

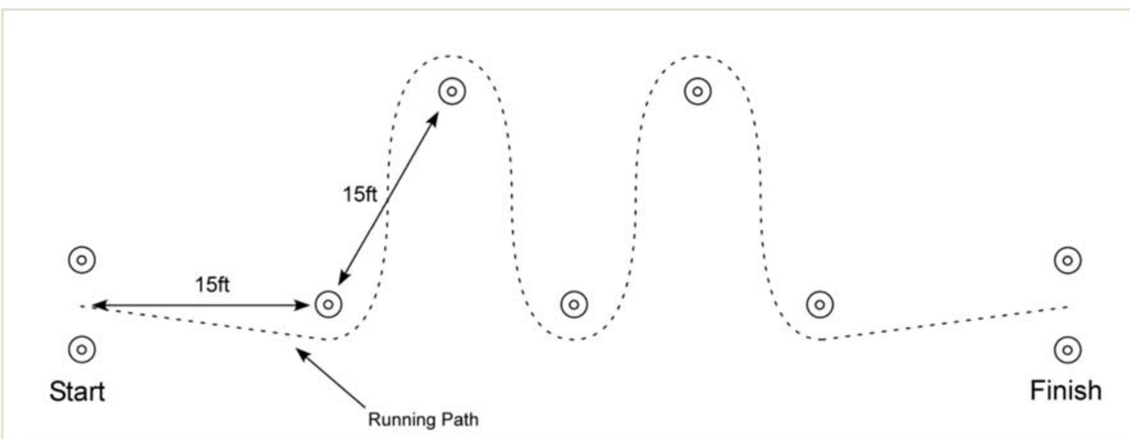


Figure 4: *Schematic of the zigzag course used for agility testing.*

With the exception of time to complete the course, all performance metrics were calculated at the three sharpest turns, which occurred sequentially in the center of the agility course (Figures 4 and 5). Custom algorithms resolved the orientation of the sacral-mounted IMU to obtain direction cosine matrices that defined the orientation of the sensor axes relative to the course-fixed axes. Performance metrics were examined with respect to the anteroposterior (A-P) sensor axis in addition to the normal, tangential, and vertical course-fixed axes (Figure 4). The algorithms require participants to remain stationary at the starting and finishing gates. This constraint was essential in order for the algorithms to accurately negate drift error resulting from the raw signal integration process. Therefore, participants started from a completely stationary position and, once through the finish gate, came to a complete stop and maintained a stationary position.

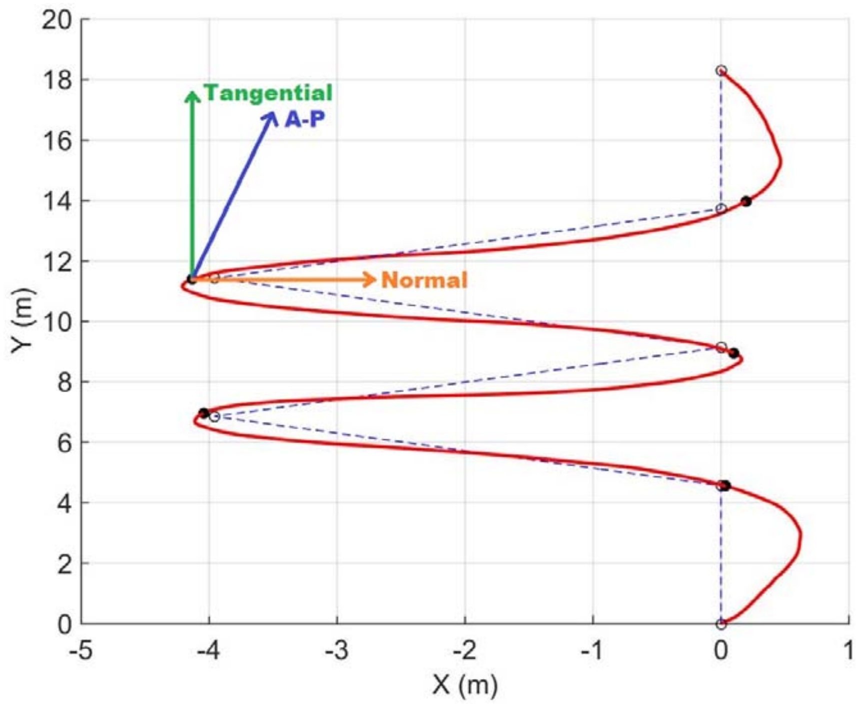


Figure 5: *Sample drift-corrected trajectory of the sacral IMU (red) relative to the straight line course between the cones (blue). Empty circles indicate cone locations and filled circles designate turn locations as determined by the custom algorithms. Performance metrics were calculated at the locations of the three sharpest turns in the center of the course.*

2.3.4.2 Procedure

Whether the MOLLE or the LP pack condition was worn at the first or the second session of agility testing was determined randomly for each participant. At the beginning of each session, prior to donning any equipment, participants ran the agility course three to five times at less than maximal effort for warm-up and familiarization. Once the IMU had been put in place and the equipment for the pack condition had been donned, participants again performed three to five sub-maximal practice runs. Once all practice runs had been completed and participants indicated they were comfortable with both the course set-up and the equipment configuration, participants performed three consecutive, maximal-effort runs through the agility course (Figure 4). Participants were allowed a 3 to 5 min rest between runs. A mean for each performance measure was obtained over a participant's three runs and used in subsequent statistical analyses. The human factors questionnaire was administered at the completion of the last maximal effort run (Hennessy, 2015).

2.4 Statistical Analysis

Statistical analyses were accomplished using IBM SPSS Statistics 21.0 (IBM, Inc., Armonk, NY). Descriptive statistics (means and *SD*s) were calculated for participants' age, height, weight, and time in service. Individual analyses of variance (ANOVAs) were carried out on the dependent measures obtained from the treadmill walking and the agility run testing. For all ANOVAs, alpha was set at .05. Mauchly's test of sphericity was applied. For sets of data that did not meet the sphericity assumption, the Greenhouse-Geisser adjustment was applied to the degrees of freedom.

Biomechanical and physiological dependent measures for the treadmill walking trials conducted at 1.34 $m \cdot s^{-1}$ (3.0 $mi \cdot h^{-1}$) were submitted to two-factor repeated measures ANOVAs with two pack types (MOLLE, LP) and three treadmill grades (0%, 5%, -5%) to determine main effects of pack type and treadmill grade and also to capture any interaction effects between pack type and grade. Two-factor repeated measures ANOVAs were also carried out on the biomechanical and physiological data acquired during treadmill walking at a 0% grade under the two speeds. These ANOVAs were of the form pack type (MOLLE, LP) by walking speed (1.34 $m \cdot s^{-1}$, 1.61 $m \cdot s^{-1}$). The Borg RPE data were analyzed using the same forms of the ANOVAs that were applied to the biomechanical and the physiological measures.

The power output data obtained from the LP during the treadmill walking trials conducted at 1.34 $m \cdot s^{-1}$ (3.0 $mi \cdot h^{-1}$) were submitted to one-factor repeated measure ANOVAs to contrast the three grade conditions (0%, 5%, -5%) in order to determine whether the power outputs were significantly affected by treadmill grade. Power outputs from the LP when the treadmill grade was set to 0% were also submitted to a one-factor repeated measure ANOVAs to contrast the two speed conditions (1.34 $m \cdot s^{-1}$, 1.61 $m \cdot s^{-1}$).

For the dependent measures obtained during the agility run, one-factor repeated measures ANOVAs were carried out to contrast the two pack types (MOLLE, LP). Power output data were not captured during the agility run.

In those instances in which an ANOVA yielded a significant main effect, post hoc tests were carried out with the significance level set at .05. A step-up sequential Bonferroni correction was used to make corrections for multiple comparisons (Hommel, 1988).

3. RESULTS

3.1 Treadmill Walking at a Speed of 1.34 m·s^{-1} on 0%, 5%, and -5% Grades

For the biomechanical and physiological dependent measures obtained during treadmill walking at 1.34 m·s^{-1} (3.0 mi·h^{-1}), the ANOVA results are reported for pack type, grade, and the interaction between these two variables. Note that ANOVA results are reported as the means across a given factor or variable. For example, means for a given pack type include all conditions in which that pack type was used, regardless of treadmill grade, while means for a given treadmill grade include all conditions in which that treadmill grade was used, regardless of pack type. Because a comparison of grade conditions (0% vs. 5% vs. -5%) was not the focus of this evaluation, post hoc findings are not presented in instances in which the grade main effect was significant and the text does not address results for the grade variable.

Additional findings related to the treadmill walking results are presented in Appendix B. The appendix contains plots of time series data for select biomechanical variables.

3.1.1 Kinetics

3.1.1.1 GRF

Summary statistics for the GRF variables are presented in Tables 4 and 5. The ANOVAs performed on the GRF measures normalized to body weight did not yield any significant main effects of pack type or significant interactions. The ANOVAs carried out on the GRF variables normalized to total weight also failed to yield any significant effects of pack type or significant interactions.

Although the pack type effect was not significant, the LP did yield somewhat higher mean vertical force than the MOLLE at heel strike (1st peak vertical) and at mid-stance and somewhat lower mean vertical force than the MOLLE at toe-off (2nd peak vertical). These relationships between the packs were obtained for GRF normalized to body weight and normalized to total weight (Tables 4 and 5).

Time-series plots of vertical GRFs for the two packs and three treadmill grades are presented in Appendix B.

Table 4: *Means (SE) of GRF measures normalized to body weight ($N \cdot kg^{-1}$) for each pack type and treadmill grade at a walking speed of 1.34 $m \cdot s^{-1}$.*

	Pack Type		**Treadmill Grade**		
GRF Measure	**MOLLE**	**LP**	**0%**	**5%**	**-5%**
1st Peak Vertical	1.73 (0.08)	1.82 (0.11)	1.67 (0.13)	1.84 (0.10)	1.82 (0.04)
2nd Peak Vertical	1.57 (0.07)	1.45 (0.08)	1.49 (0.11)	1.43 (0.07)	1.61 (0.04)
Peak Mid-stance	1.00 (0.04)	1.07 (0.07)	1.02 (0.08)	1.06 (0.06)	1.03 (0.03)
Peak Braking	-0.30 (0.02)	-0.29 (0.02)	-0.28 (0.02)	-0.30 (0.02)	-0.30 (0.01)
Peak Propulsive	0.31 (0.01)	0.30 (0.01)	0.29 (0.02)	0.32 (0.02)	0.30 (0.01)
1st Peak Medial	0.11 (0.01)	0.12 (0.01)	0.11 (0.01)	0.12 (0.01)	0.12 (0.01)
2nd Peak Medial	0.12 (0.01)	0.10 (0.01)	0.10 (0.01)	0.10 (0.01)	0.10 (0.01)
Peak Lateral[a]	-0.06 (0.01)	-0.06 (0.01)	-0.06 (0.01)	-0.05 (0.01)	-0.07 (0.01)

[a]Significant main effect of treadmill grade, $p < .05$ or better.

Table 5: *Means (SE) of GRF measures normalized to total weight (N·kg^{-1}) for each pack type and treadmill grade at a walking speed of 1.34 m·s^{-1}.*

	Pack Type		**Treadmill Grade**		
GRF Measure	**MOLLE**	**LP**	**0%**	**5%**	**-5%**
1st Peak Vertical	1.07 (0.05)	1.09 (0.07)	1.02 (0.08)	1.12 (0.06)	1.10 (0.02)
2nd Peak Vertical	0.97 (0.04)	0.87 (0.05)	0.91 (0.07)	0.87 (0.05)	0.98 (0.03)
Peak Mid-stance	0.62 (0.03)	0.64 (0.05)	0.62 (0.05)	0.64 (0.04)	0.62 (0.02)
Peak Braking	-0.18 (0.01)	-0.17 (0.01)	-0.17 (0.01)	-0.18 (0.01)	-0.18 (0.01)
Peak Propulsive	0.19 (0.01)	0.18 (0.01)	0.18 (0.01)	0.19 (0.01)	0.18 (0.01)
1st Peak Medial	0.07 (0.01)	0.07 (0.01)	0.06 (0.01)	0.07 (0.01)	0.07 (0.01)
2nd Peak Medial	0.07 (0.01)	0.06 (0.01)	0.06 (0.01)	0.06 (0.01)	0.06 (0.01)
Peak Lateral[a]	-0.04 (0.00)	-0.04 (0.00)	-0.04 (0.00)	-0.03 (0.00)	-0.04 (0.01)

. [a]Significant main effect of treadmill grade, $p < .05$ or better.

<u>*3.1.1.2 Sagittal Plane Joint Moments*</u>

Table 6 gives the means and standard errors of the joint moments for the hip, knee, and ankle. The ANOVAs did not yield significant interactions for any of the joint moment variables. However, there was a significant main effect of pack type on maximum hip moment ($p = .004$) and minimum ankle moment ($p = .015$). When the LP system was used, maximum (extension) hip joint moment was 9.4% lower and minimum (dorsiflexion) ankle joint moment was 18.2% less compared to the values for the MOLLE.

Time-series plots of the hip and ankle joint moments for each pack type and treadmill grade are presented in Appendix B.

Table 6: *Means (SE) of maximum and minimum joint moments (N·m) at the hip, knee, and ankle for each pack type and treadmill grade at a walking speed of 1.34 m·s⁻¹.*

	Pack Type		Treadmill Grade		
Joint Moment Variable	**MOLLE**	**LP**	**0%**	**5%**	**-5%**
Maximum Hip Moment[a]	0.78 (0.03)	0.71 (0.04)	0.78 (0.05)	0.72 (0.04)	0.72 (0.05)
Minimum Hip Moment[b]	-1.00 (0.04)	-1.07 (0.05)	-1.01 (0.06)	-0.86 (0.04)	-1.22 (0.03)
Maximum Knee Moment[b]	0.46 (0.02)	0.46 (0.02)	0.47 (0.03)	0.42 (0.02)	0.49 (0.01)
Minimum Knee Moment[b]	-0.84 (0.05)	-0.89 (0.06)	-0.76 (0.06)	-0.78 (0.06)	-1.05 (0.04)
Maximum Ankle Moment[b]	1.31 (0.06)	1.23 (0.06)	1.27 (0.08)	1.16 (0.07)	1.37 (0.03)
Minimum Ankle Moment[a,b]	-0.18 (0.01)	-0.15 (0.01)	-0.17 (0.01)	-0.19 (0.01)	-0.14 (0.01)

[a]Significant main effect of pack type, $p < .05$ or better. [b]Significant main effect of treadmill grade, $p < .05$ or better.

3.1.1.3 Loading Rate

The means and standard errors for the loading rate variables normalized to body weight and normalized to total weight are presented in Tables 7 and 8, respectively. The ANOVAs performed on the loading rate measures did not yield significant main effects or significant interactions.

Table 7: *Means (SE) of the mean and instantaneous loading rates (kg·s⁻¹) normalized to body weight for each pack type and treadmill grade at a walking speed of 1.34 m·s⁻¹.*

	Pack Type		Treadmill Grade		
Loading Rate Variable	**MOLLE**	**LP**	**0%**	**5%**	**-5%**
Mean Loading Rate	10.40 (0.65)	10.27 (0.66)	9.72 (0.78)	10.73 (0.73)	10.56 (0.47)
Instantaneous Peak Loading Rate	22.27 (1.18)	21.69 (1.43)	20.74 (1.71)	21.72 (1.54)	23.48 (0.74)

Table 8: *Means (SE) of the mean and instantaneous loading rates (kg·s⁻¹) normalized to total weight for each pack type and treadmill grade at a walking speed of 1.34 m·s⁻¹.*

	Pack Type		Treadmill Grade		
Loading Rate Variable	**MOLLE**	**LP**	**0%**	**5%**	**-5%**
Mean Loading Rate	6.40 (0.39)	6.13 (0.39)	5.89 (0.47)	6.50 (0.44)	6.39 (0.26)
Instantaneous Peak Loading Rate	13.70 (0.72)	12.96 (0.87)	12.59 (1.04)	13.18 (0.94)	14.22 (0.41)

3.1.2 Kinematics

3.1.2.1 Hip Angle

Table 9 presents the means and standard errors of the hip angle measures. There was a significant main effect of pack type on both the maximum (p = .0001) and the minimum hip (p = .0001) angles. Maximum hip angle (hip flexion) and minimum hip angle (hip extension) were significantly greater when the LP was carried compared to the MOLLE. There was no significant effect of pack type on hip ROM. This suggests that the hip remained in a more flexed position throughout the gait cycle when the LP was worn compared with the MOLLE.

Time-series plots of the hip angle for each pack type and treadmill grade are presented in Appendix B.

Table 9: *Means (SE) of the hip angle variables (degrees) for each pack type and treadmill grade at a walking speed of 1.34 m·s⁻¹.*

	Pack Type		Treadmill Grade		
Hip Angle Variable	**MOLLE**	**LP**	**0%**	**5%**	**-5%**
Maximum Hip Angle[a,b]	54.45 (1.37)	62.81 (1.38)	56.70 (1.45)	50.89 (1.31)	68.30 (1.33)
Minimum Hip Angle[a,b]	1.97 (1.58)	9.44 (1.27)	4.80 (1.44)	3.34 (1.15)	8.96 (1.64)
Hip ROM[b]	52.49 (1.20)	53.37 (0.95)	51.90 (1.21)	47.55 (0.97)	59.34 (1.16)

[a]Significant main effect of pack type, $p < .05$ or better. [b]Significant main effect of treadmill grade, $p < .05$ or better.

3.1.2.2 Knee Angle

The ANOVAs carried out on the knee angle variables did not yield any significant main effects of pack type or significant interactions. The means and the standard errors for the knee angle variables are presented in Table 10.

Table 10: *Means (SE) of the knee angle variables (degrees) for each pack type and treadmill grade at a walking speed of 1.34 m·s*$^{-1}$.

	Pack Type		Treadmill Grade		
Knee Angle Variable	**MOLLE**	**LP**	**0%**	**5%**	**-5%**
Maximum Knee Angle[a]	70.70 (1.55)	71.07 (1.35)	70.10 (1.35)	71.74 (1.37)	70.80 (1.31)
Minimum Knee Angle	-0.80 (1.28)	-0.36 (1.16)	-0.99 (1.03)	0.42 (1.13)	-1.17 (1.18)
Knee ROM	71.50 (0.90)	71.42 (0.99)	71.09 (0.92)	71.32 (0.92)	71.97 (1.18)

[a]Significant main effect of treadmill grade, *p* < .05 or better.

3.1.2.3 Ankle Angle

There were no significant main effects of pack type or significant interactions obtained in the analyses of the ankle angle measures. Table 11 contains the means and standard errors for the ankle angle variables.

Table 11: *Means (SE) of the ankle angle variables (degrees) for each pack type and treadmill grade at a walking speed of 1.34 m·s*$^{-1}$.

	Pack Type		Treadmill Grade		
Ankle Angle Variable	**MOLLE**	**LP**	**0%**	**5%**	**-5%**
Maximum Ankle Angle[a]	12.84 (1.09)	12.46 (0.82)	11.81 (1.03)	11.79 (0.92)	14.36 (0.80)
Minimum Ankle Angle[a]	-16.61 (1.58)	-16.94 (1.67)	-17.73 (1.64)	-16.11 (1.51)	-16.48 (1.62)
Ankle ROM[a]	29.45 (1.04)	29.41 (1.35)	29.54 (1.18)	27.90 (1.13)	30.83 (1.43)

[a]Significant main effect of treadmill grade, *p* < .05 or better

3.1.2.4 Trunk Angle

The ANOVAs performed on the trunk angle variables did not reveal any significant interactions. However, pack type did have a significant main effect on the maximum ($p < .0001$) and the minimum trunk angle ($p < .0001$) and the trunk ROM ($p = .013$) variables. When the LP was worn, maximum forward trunk lean was 67% greater and trunk ROM was 25% less than it was with the MOLLE. Further, the minimum forward trunk lean value with the LP was double the value with the MOLLE. The means and standard errors for the trunk angle variables are in Table 12. Time-series plots of trunk angle for each pack type and treadmill grade are presented in Appendix B.

Table 12: *Means (SE) of the trunk angle variables (degrees) for each pack type and treadmill grade at a walking speed of 1.34 m·s⁻¹.*

	Pack Type		Treadmill Grade		
Trunk Angle Variable	**MOLLE**	**LP**	**0%**	**5%**	**-5%**
Maximum Trunk Angle[a,b]	11.60 (0.79)	19.34 (0.97)	14.80 (0.86)	12.40 (0.75)	19.22 (0.97)
Minimum Trunk Angle[a,b]	7.84 (0.75)	16.42 (0.84)	11.34 (0.76)	9.50 (0.72)	15.55 (0.95)
Trunk ROM[a,b]	3.77 (0.10)	2.92 (0.25)	3.46 (0.18)	2.90 (0.14)	3.68 (0.13)

[a]Significant main effect of pack type, $p < .05$ or better. [b]Significant main effect of treadmill grade, $p < .05$ or better.

<u>*3.1.2.5 Spatiotemporal Gait Parameters*</u>

There were no significant main effects of pack type or significant interactions in the analyses performed on the spatiotemporal gait parameters. The means and standard errors for all parameters are in Table 13.

Table 13: *Means (SE) of the spatiotemporal gait parameters for each pack type and treadmill grade at a walking speed of 1.34 m·s⁻¹.*

	Pack Type		Treadmill Grade		
Parameter	**MOLLE**	**LP**	**0%**	**5%**	**-5%**
Stride Length (m)	1.02 (0.01)	1.02 (0.01)	1.03 (0.02)	1.02 (0.01)	1.02 (0.02)
Stride Width (m)	0.16 (0.01)	0.16 (0.01)	0.16 (0.01)	0.16 (0.01)	0.16 (0.01)
Stride Time (s)	0.52 (0.01)	0.52 (0.01)	0.53 (0.01)	0.52 (0.01)	0.52 (0.01)
Stance Duration[a] **(% stride time)**	65.08 (0.49)	65.27 (0.45)	64.99 (0.59)	64.37 (0.35)	66.17 (0.46)
Swing Duration[a] **(% stride time)**	34.92 (0.49)	34.73 (0.45)	35.01 (0.59)	35.63 (0.35)	33.83 (0.46)
Double Support Duration[a] **(% stride time)**	30.20 (1.02)	30.59 (0.90)	30.01 (1.20)	28.81 (0.74)	32.36 (0.93)

[a]Significant main effect of treadmill grade, $p < .05$ or better.

3.1.3 Metabolics

There was a significant pack type by treadmill grade interaction effect (p = .00007) on respiratory quotient (R), which is plotted in Figure 6. At the -5% and the 0% grades, the R values were highly similar for the LP and the MOLLE packs. However, at the 5% grade, carrying the LP resulted in an R value that was 7.1% higher than the R value obtained when carrying the MOLLE. Respiratory quotient was the only metabolic variable for which a significant interaction was obtained.

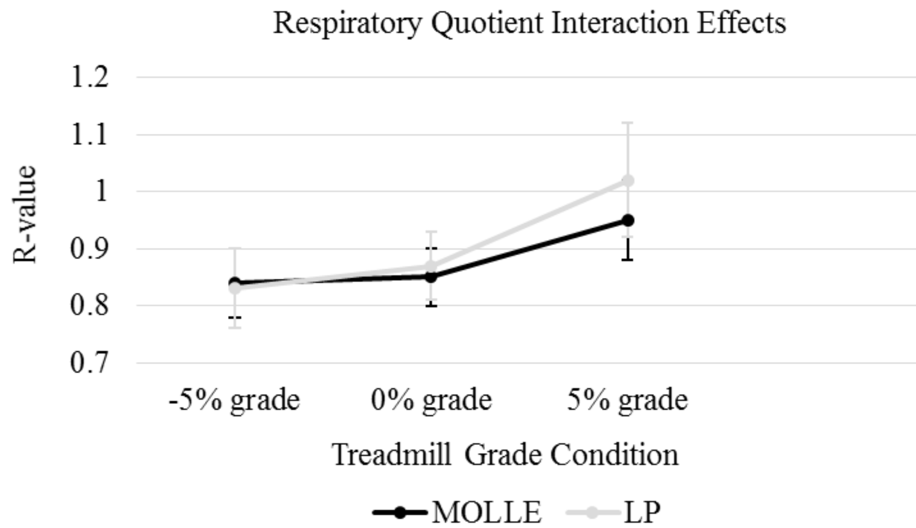


Figure 6: *Mean (±1 SD) respiratory quotient values for each pack type at the -5%, 0%, and 5% treadmill grades and a walking speed of 1.34 $m \cdot s^{-1}$.*

Means and standard errors for the metabolic variables are in Table 14. There was a significant main effect of pack type on $\dot{V}O_2$ expressed in absolute units, normalized by body weight, and normalized by total weight. In each instance, the value for the LP was greater than the value for the MOLLE. For $\dot{V}O_2$ expressed in absolute units and normalized by body weight, the value for the LP exceeded that for the MOLLE by 11%. For $\dot{V}O_2$ normalized by total weight, the value for the LP was 6% greater than the value for the MOLLE. Pack type was also found to be significant in the analyses of HR and of RPE. Heart rate was 8% higher with the LP than with the MOLLE and the RPE was 10% higher.

Table 14: *Means (SE) of the metabolic variables for each pack type and treadmill grade at a walking speed of 1.34 m·s⁻¹.*

	Pack Type		**Treadmill Grade**		
Parameter	**MOLLE**	**LP**	**0%**	**5%**	**-5%**
$\dot{V}O_2$[a,b] **($ml \cdot min^{-1}$)**	2225.32 (78.71)	2467.81 (66.01)	2227.74 (79.62)	3129.12 (69.24)	1682.84 (80.55)
$\dot{V}O_2$ normalized to body weight[a,b] **($ml \cdot kg^{-1} \cdot min^{-1}$)**	26.59 (1.08)	29.55 (1.00)	26.68 (1.08)	37.44 (1.07)	20.09 (1.07)
$\dot{V}O_2$ normalized to total weight[a,b] **($ml \cdot kg^{-1} \cdot min^{-1}$)**	17.10 (0.60)	18.14 (0.49)	16.72 (0.60)	23.50 (0.52)	12.63 (0.61)
R[a,b,c]	0.88 (0.01)	0.91 (0.02)	0.86 (0.02)	0.98 (0.02)	0.83 (0.02)
HR[a,b] **(bpm)**	135.65 (3.72)	146.22 (4.82)	138.98 (4.99)	161.25 (4.77)	122.58 (4.60)
RPE[a,b]	9.89 (0.46)	10.89 (0.60)	9.67 (0.52)	12.33 (0.65)	9.17 (0.54)

[a]Significant main effect of pack type, $p < .05$ or better. [b]Significant main effect of treadmill grade, $p < .05$ or better. [c]Significant pack type by treadmill grade interaction, $p < .05$ or better.

3.1.4 LP Measurements

Table 15 presents the means and standard errors of the power outputs, in Watts (W), of the LP at each grade. For convenience, the equivalent energy is also presented in Watt·hours (W·h), Joules (J), and kilocalories (kcal). There was a significant main effect of treadmill grade ($p = .027$) on power output of the LP system. Power output was significantly higher ($p = .023$) during walking at the 5% grade than during walking at the 0% grade. There was no significant difference in power outputs between the 0% grade and the -5% grade ($p = .676$) or between the 5% grade and the -5% grade ($p = 0.50$). Means and standard errors of the pack displacement at each grade are also presented in Table 15. The ANOVA did not reveal a significant effect of treadmill grade on pack displacement.

Table 15: *Mean (SE) power and energy outputs and pack displacements of the LP for each treadmill grade at a walking speed of 1.34 m·s^{-1}.*

	Treadmill Grade		
Variable	**0%**	**5%**	**-5%**
Power (W)	5.56 ^{A} (1.70)	6.82 ^{B} (2.60)	6.06 ^{AB} (1.57)
Energy (W·h)	0.19 (0.06)	0.23 (0.09)	0.21 (0.05)
Energy (J)	688 (205)	840 (310)	746 (187)
Energy (kcal)	0.16 (0.05)	0.20 (0.07)	0.18 (0.04)
Pack Displacement (m)	0.045 ^{A} (0.005)	0.051 ^{A} (0.007)	0.046 ^{A} (0.006)

Note. Values that share a superscript with the same letter do not differ significantly from one another ($p > .05$). Values that do not share a superscript with the same letter differ significantly ($p < .05$) from one another.

3.2 Treadmill Walking on a 0% Grade at Speeds of 1.34 m·s^{-1} and 1.61 m·s^{-1}

For the biomechanical and physiological dependent measures obtained during treadmill walking at 1.34 m·s^{-1} vs. 1.61 m·s^{-1} on a 0% grade, the ANOVA results are reported for pack type, speed, and the interaction between these two variables. Note that ANOVA results are reported as the means across a given factor. For example, means for a given pack type include all conditions in which that pack type was used, regardless of walking speed, while means for a given walking speed include all conditions in which that walking speed was used, regardless of pack type. Because a comparison of walking speeds (1.34 m·s^{-1} vs. 1.61 m·s^{-1}) was not the focus of this evaluation, the text does not address results for the walking speed variable.

Additional findings related to the results for treadmill walking are presented in Appendix C. The appendix contains plots of time series data for select biomechanical variables.

3.2.1 Kinetics

3.2.1.1 GRF

The analyses of peak braking force normalized to body weight ($p = .010$) and normalized to total weight ($p = .007$) both yielded a significant interaction between pack type and walking speed (Figure 7). These were the only interactions that were significant in the analyses of the GRF variables. The significant interactions indicated that peak braking forces with the MOLLE and the LP were essentially equal at the speed of 1.34 m·s^{-1} (3.0 mi·h^{-1}). However, at the faster speed of 1.61 m·s^{-1} (3.6 mi·h^{-1}), the peak braking force with the MOLLE was higher than the force with the LP (Figure 7).

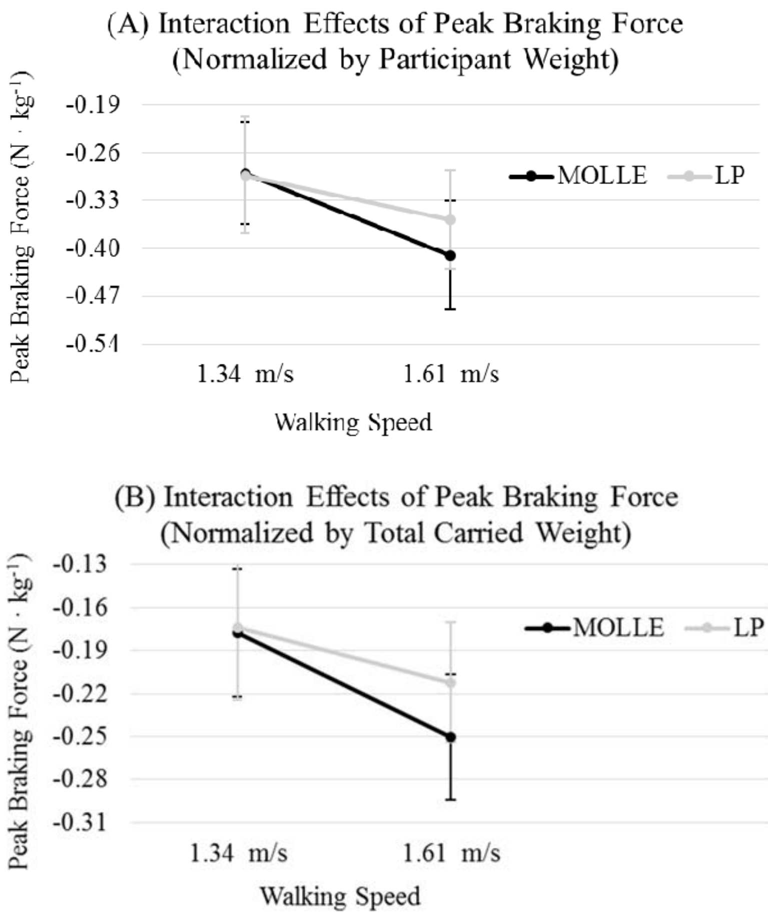


Figure 7: *Mean values (±1 SD) for peak braking force (A) normalized to body weight and (B) normalized to total weight for each pack type and walking speed at a 0% grade.*

There were a number of significant main effects of pack type in the ANOVAs performed on the GRF variables normalized to body weight. The means and standard errors for these GRF variables are in Table 16, and the significant main effects of pack are also indicated there. Compared with the MOLLE values, peak toe-off force (2nd peak vertical force; $p = .041$) was lower by 8.9%, peak braking force ($p = .023$) lower by 5.9%, peak propulsive force ($p = .03$) lower by 8.7%, and 2nd peak medial force ($p < .0001$) lower by 9.5% when the LP was used. The LP was also associated with somewhat higher mean vertical force at heel strike (1st peak vertical) and somewhat lower mean vertical force at mid-stance than the MOLLE, although these variables were not significantly affected by pack type (Table 16).

Table 16: *Means (SE) of GRF measures normalized to body weight ($N \cdot kg^{-1}$) for each pack type and walking speed at a 0% grade.*

	Pack Type		**Walking Speed ($m \cdot s^{-1}$)**	
GRF Measure	**MOLLE**	**LP**	**1.34**	**1.61**
1st Peak Vertical[b]	1.88 (0.08)	1.94 (0.11)	1.70 (0.12)	2.12 (0.08)
2nd Peak Vertical[a]	1.65 (0.07)	1.51 (0.10)	1.53 (0.11)	1.62 (0.06)
Peak Mid-stance[b]	0.90 (0.03)	0.10 (0.06)	1.02 (0.07)	0.90 (0.03)
Peak Braking[a,b,c]	-0.35 (0.02)	-0.33 (0.02)	-0.29 (0.02)	-0.38 (0.02)
Peak Propulsive[a,b]	0.36 (0.02)	0.33 (0.02)	0.30 (0.02)	0.39 (0.01)
1st Peak Medial[b]	0.12 (0.01)	0.12 (0.01)	0.11 (0.01)	0.13 (0.01)
2nd Peak Medial[a]	0.11 (0.01)	0.10 (0.01)	0.10 (0.01)	0.10 (0.01)
Peak Lateral[b]	-0.07 (0.01)	-0.07 (0.01)	-0.06 (0.01)	-0.07 (0.01)

[a]Significant main effect of pack type, $p < .05$ or better. [b]Significant main effect of walking speed, $p < .05$ or better. [c]Significant pack type by walking speed interaction, $p < .05$ or better.

When the GRF variables were normalized to total weight, the analyses revealed a significant main effect of pack type on peak toe-off (2nd peak vertical force; $p = .010$), peak braking ($p = .009$), peak propulsive ($p = .006$), and 2nd peak medial ($p < .0001$) forces. The means and standard errors for the GRF variables normalized to total weight are in Table 17. With the LP system, peak toe-off force (2nd peak vertical force) was lower by 12.6%, peak braking force by 10.0%, peak propulsive force by 9.5%, and 2nd peak medial force by 15.4% compared to the MOLLE. In addition, the LP system produced somewhat higher forces at mid-stance than the MOLLE, although pack type did not have a significant effect on peak mid-stance force.

Time-series plots of vertical GRFs normalized to body weight and normalized to total weight for the two packs and two treadmill speeds are presented in Appendix C.

Table 17: *Means (SE) of GRF measures normalized to total weight (N·kg-1) for each pack type and walking speed at a 0% grade.*

	Pack Type		Walking Speed (m·s^{-1})	
GRF Measure	**MOLLE**	**LP**	**1.34**	**1.61**
1st Peak Vertical[b]	1.15 (0.05)	1.15 (0.07)	1.03 (0.07)	1.27 (0.04)
2nd Peak Vertical[a]	1.01 (0.04)	0.89 (0.06)	0.93 (0.06)	0.98 (0.04)
Peak Mid-stance[b]	0.56 (0.02)	0.59 (0.04)	0.62 (0.04)	0.53 (0.02)
Peak Braking[a,b,c]	-0.21 (0.01)	-0.19 (0.01)	-0.18 (0.01)	-0.23 (0.01)
Peak Propulsive[a,b]	0.22 (0.01)	0.20 (0.01)	0.18 (0.01)	0.24 (0.01)
1st Peak Medial[b]	0.08 (0.01)	0.07 (0.01)	0.07 (0.01)	0.08 (0.01)
2nd Peak Medial[a]	0.07 (0.01)	0.06 (0.01)	0.06 (0.01)	0.06 (0.01)
Peak Lateral[b]	-0.04 (0.01)	-0.04 (0.01)	-0.04 (0.00)	-0.05 (0.01)

[a]Significant main effect of pack type, $p < .05$ or better. [b]Significant main effect of walking speed, $p < .05$ or better. [c]Significant pack type by walking speed interaction, $p < .05$ or better.

<u>*3.2.1.2 Sagittal Plane Joint Moments*</u>

Table 18 gives the means and standard errors of the joint moments for the hip, knee, and ankle. All joint moments were measured in the sagittal plane. There was a significant pack type by walking speed interaction on both the maximum hip moment ($p = .020$) and the minimum knee moment variables ($p = .037$; Figure 8). With regard to the maximum hip moment, the mean values for the LP were highly similar for the two walking speeds, whereas the mean value for the MOLLE was higher at 1.61 m·s^{-1} than at 1.34 m·s^{-1} (Figure 8). For the minimum knee movement interaction, the values for both pack types were higher at 1.34 m·s^{-1} than at 1.61 m·s^{-1}. However, the LP mean value decreased less than the MOLLE value at the 1.61 m·s^{-1} speed (Figure 8).

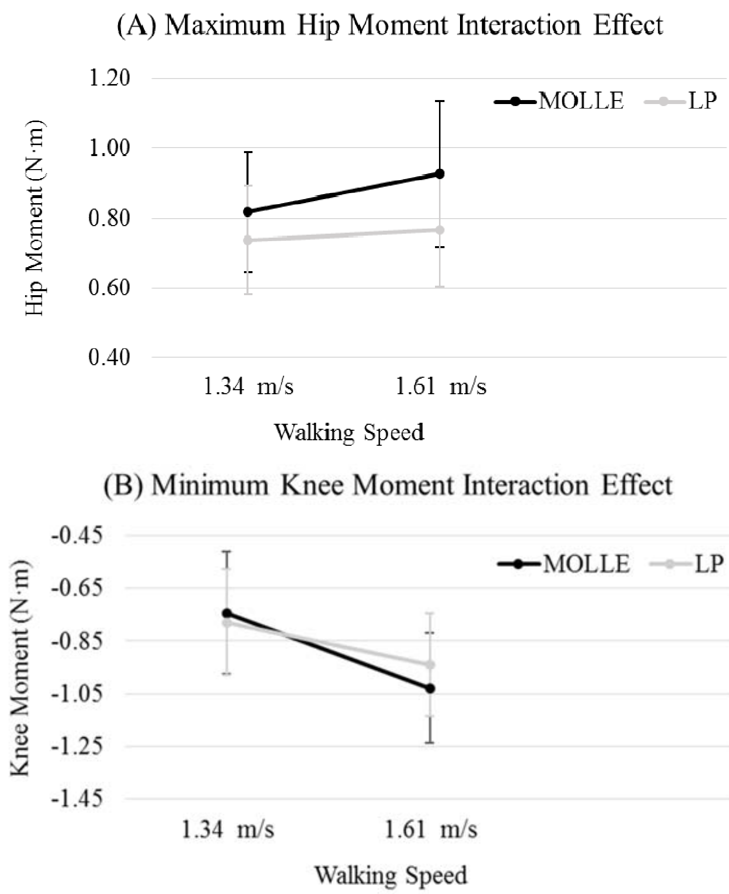


Figure 8: *Mean values (±1 SD) for (A) maximum hip and (B) minimum knee joint moments for each pack type at walking speeds of 1.34 and 1.61 m·s*$^{-1}$ *on a 0% grade. There was a significant interaction of pack type and walking speed on both maximum hip moment (p = .020) and minimum knee moment (p = .037).*

In addition to the two significant interactions, there was a significant main effect of pack type on the maximum hip moment (p = .001) and the maximum (p = .034) and minimum (p = .003) ankle moments (Table 18). Compared with the MOLLE, maximum hip moment was 14.8% lower, maximum ankle moment was 14.1% lower, and minimum ankle moment was 30% lower when the LP was used (Table 18).

Table 18: *Means (SE) of maximum and minimum joint moments (N·m) at the hip, knee, and ankle for each pack type and walking speed at a 0% grade.*

	Pack Type		**Walking Speed ($m \cdot s^{-1}$)**	
Joint Moment Variable	**MOLLE**	**LP**	**1.34**	**1.61**
Maximum Hip Moment[a,b,c]	0.87 (0.05)	0.75 (0.04)	0.78 (0.05)	0.85 (0.05)
Minimum Hip Moment[b]	-1.15 (0.05)	-1.19 (0.06)	-1.01 (0.06)	-1.33 (0.05)
Maximum Knee Moment[b]	0.53 (0.03)	0.50 (0.02)	0.47 (0.03)	0.56 (0.02)
Minimum Knee Moment[b,c]	-0.89 (0.06)	-0.86 (0.06)	-0.76 (0.06)	-0.98 (0.05)
Maximum Ankle Moment[a]	1.44 (0.08)	1.25 (0.08)	1.27 (0.08)	1.42 (0.07)
Minimum Ankle Moment[a,b]	-0.23 (0.01)	-0.17 (0.01)	-0.17 (0.01)	-0.23 (0.01)

[a]Significant main effect of pack type, $p < .05$ or better. [b]Significant main effect of walking speed, $p < .05$ or better. [c]Significant pack type by walking speed interaction, $p < .05$ or better.

3.2.1.3 Loading Rate

The means and standard errors for the loading rate variables normalized to body weight and normalized to total weight are presented in Tables 19 and 20, respectively. There were no significant main effects of pack type on the loading rate variables (Tables 19 and 20). However, the interaction between pack type and walking speed was significant ($p = .047$) on the instantaneous peak loading rate adjusted for body weight variable (Figure 9). The values for the MOLLE and the LP were similar at 1.34 $m \cdot s^{-1}$ (3.0 $m \cdot h^{-1}$). However, at the speed of 1.61 $m \cdot s^{-1}$ (3.6 $m \cdot h^{-1}$), peak loading rate was lower for the LP (Figure 9).

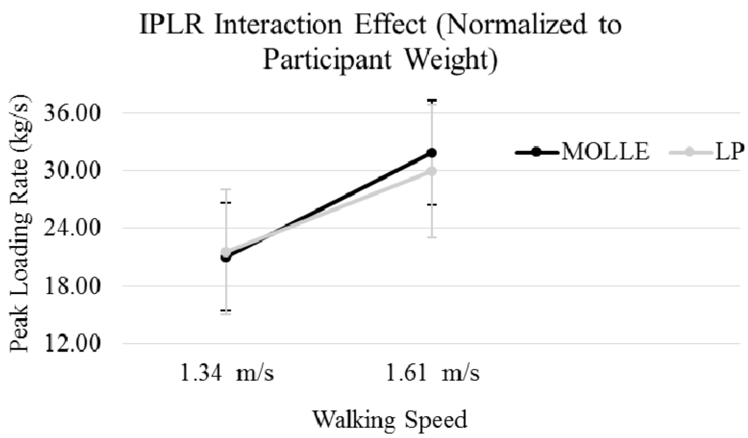


Figure 9: *Mean values (±1 SD) for instantaneous peak loading rate for each pack type at the 1.34 and the 1.61 $m \cdot s^{-1}$ walking speeds on a 0% grade.*

Table 19: *Means (SE) of the mean and instantaneous loading rates (kg·s^{-1}) normalized to body weight for each pack type and walking speed at a 0% grade.*

	Pack Type		**Walking Speed (m·s^{-1})**	
Loading Rate Variable	**MOLLE**	**LP**	**1.34**	**1.61**
Mean Loading Rate[a]	12.88 (0.71)	12.44 (0.91)	9.90 (0.73)	15.42 (0.91)
Instantaneous Peak Loading Rate[a,b]	26.45 (1.48)	25.78 (1.86)	21.31 (1.66)	30.92 (1.72)

[a]Significant main effect of walking speed, $p < .05$ or better. [b]Significant pack type by walking speed interaction, $p < .05$ or better.

Table 20: *Means (SE) of the mean and instantaneous loading rates (kg·s^{-1}) normalized to total weight for each pack type and walking speed at a 0% grade.*

	Pack Type		**Walking Speed (m·s^{-1})**	
Loading Rate Variable	**MOLLE**	**LP**	**1.34**	**1.61**
Mean Loading Rate[a]	7.87 (0.40)	7.36 (0.50)	5.97 (0.43)	9.27 (0.48)
Instantaneous Peak Loading Rate[a]	16.18 (0.86)	15.27 (1.07)	12.84 (0.98)	18.61 (0.95)

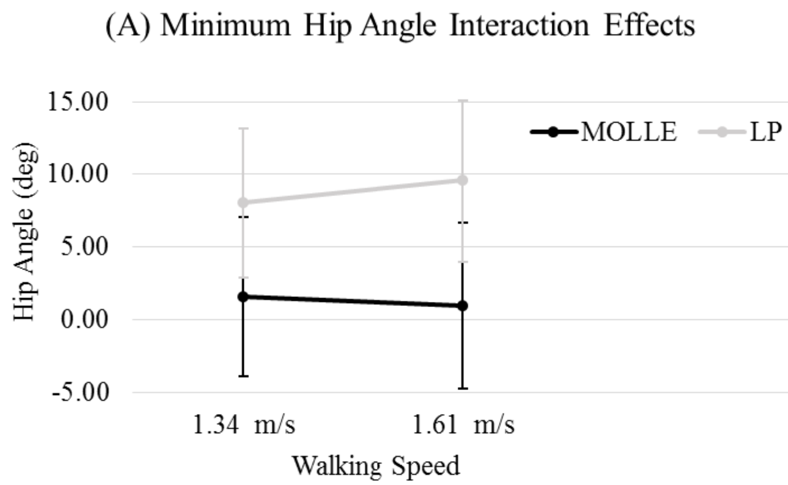
[a]Significant main effect of walking speed, $p < .05$ or better.

3.2.2 Kinematics

3.2.2.1 Hip Angle

Table 21 presents the means and standard errors of the hip angle measures. There was a significant pack type by walking speed interaction effect on both the minimum hip angle ($p = .014$) and the hip ROM variables ($p = .009$). These interactions are plotted in Figure 10. At 1.61 m·s^{-1}, the LP minimum hip angle value was higher than it was at 1.34 m·s^{-1} indicating greater flexion; the MOLLE value at 1.61 m·s^{-1} was lower than it was at 1.34 m·s^{-1} (Figure 10). With regard to the hip angle ROM interaction, the LP ROM was greater than the ROM with the MOLLE at 1.34 m·s^{-1} and both the LP and the MOLLE had about the same ROM at the higher speed (Figure 10). In addition to the significant interactions, there was a significant main effect of pack type on the maximum hip angle ($p < .0001$), minimum hip angle ($p < .0001$), and hip ROM ($p < .040$). Specifically, compared with the MOLLE, maximum hip angle was greater by 14.6%, minimum hip angle by 150.6%, and hip ROM by 1.9% with the LP (Table 21).

Time-series plots of hip angle for the two pack types and the two walking speeds are presented in Appendix C.



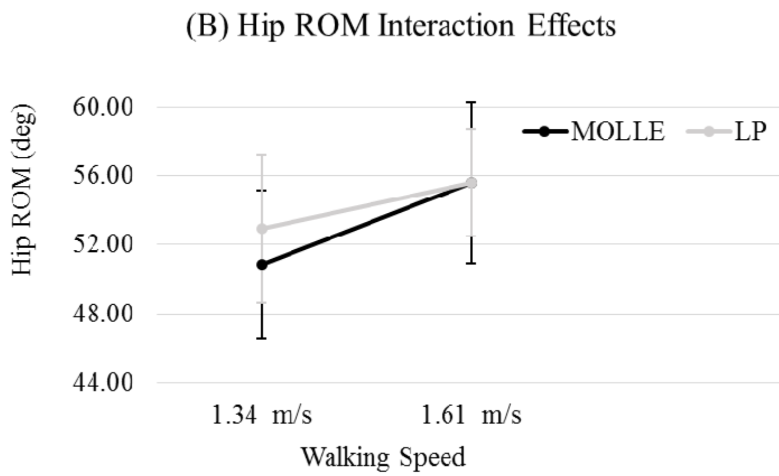


***Figure 10**: Mean values (±1 SD) for (A) minimum hip angle and (B) hip ROM for each pack type at the 1.34 and the 1.61 $m \cdot s^{-1}$ walking speeds on a 0% grade.*

***Table 21:** Means (SE) of the hip angle variables (degrees) for each pack type and walking speed at a 0% grade.*

	Pack Type		Walking Speed ($m \cdot s^{-1}$)	
Hip Angle Variable	**MOLLE**	**LP**	**1.34**	**1.61**
Maximum Hip Angle[a,b]	54.46 (1.41)	63.06 (1.69)	56.70 (1.45)	60.82 (1.61)
Minimum Hip Angle[a,c]	1.24 (1.56)	8.80 (1.49)	4.80 (1.44)	5.24 (1.57)
Hip ROM[a,b,c]	53.23 (1.27)	54.26 (1.03)	51.90 (1.21)	55.59 (1.10)

[a]Significant main effect of pack type, $p < .05$ or better. [b]Significant main effect of walking speed, $p < .05$ or better. [c]Significant pack type by walking speed interaction, $p < .05$ or better.

3.2.2.2 Knee Angle

The ANOVAs performed on the knee angle variables did not yield any significant main effects of pack type or significant interactions. Table 22 lists the means and standard errors for the knee angle variables.

Table 22: *Means (SE) of the knee angle variables (degrees) for each pack type and walking speed on a 0% grade.*

	Pack Type		Walking Speed ($m \cdot s^{-1}$)	
Knee Angle Variable	**MOLLE**	**LP**	**1.34**	**1.61**
Maximum Knee Angle	68.86 (1.49)	70.21 (1.32)	70.10 (1.35)	68.97 (1.38)
Minimum Knee Angle	-1.91 (1.22)	-1.34 (1.08)	-0.99 (1.03)	-2.26 (1.17)
Knee ROM	70.77 (0.93)	71.55 (1.11)	71.09 (0.92)	71.23 (1.07)

3.2.2.3 Ankle Angle

There were no significant main effects of pack type or significant interactions obtained in the analyses of the ankle angle measures. Table 23 contains the means and standard errors for the ankle angle variables.

Table 23: *Means (SE) of the ankle angle variables (degrees) for each pack type and walking speed at a 0% grade.*

	Pack Type		Walking Speed ($m \cdot s^{-1}$)	
Ankle Angle Variable	**MOLLE**	**LP**	**1.34**	**1.61**
Maximum Ankle Angle[a]	11.84 (1.21)	11.16 (0.92)	11.81 (1.03)	11.19 (1.02)
Minimum Ankle Angle	-17.97 (1.76)	-18.10 (1.65)	-17.73 (1.64)	-18.34 (1.68)
Ankle ROM	29.81 (1.10)	29.26 (1.22)	29.54 (1.18)	29.53 (1.16)

[a]Significant main effect of walking speed, $p < .05$ or better

3.2.2.4 Trunk Angle

Table 24 presents the means and standard errors for the trunk angle variables. The ANOVAs performed on the trunk angle variables did not reveal any significant interactions. There was a significant main effect of pack type on the maximum ($p < .0001$) and the minimum ($p < .0001$) trunk angles, as well as trunk ROM ($p < .002$; Table 24). With the LP, maximum forward trunk lean was 43.6% greater and minimum forward trunk lean was 62.2% greater than with the MOLLE. Further, trunk ROM with the LP was 24% less than with the MOLLE.

Time-series plots of trunk angle for each pack type and walking speed are presented in Appendix C.

Table 24: *Means (SE) of the trunk angle variables (degrees) for each pack type and walking speed on a 0% grade.*

	Pack Type		**Walking Speed ($m \cdot s^{-1}$)**	
Trunk Angle Variable	**MOLLE**	**LP**	**1.34**	**1.61**
Maximum Trunk Angle[a,b]	13.14 (1.02)	20.46 (1.09)	14.80 (0.86)	18.79 (1.19)
Minimum Trunk Angle[a,b]	9.17 (0.98)	17.44 (1.02)	11.34 (0.76)	15.26 (1.18)
Trunk ROM[a]	3.97 (0.15)	3.02 (0.24)	3.46 (0.18)	3.53 (0.18)

[a]Significant main effect of pack type, $p < .05$ or better. [b]Significant main effect of walking speed, $p < .05$ or better

3.2.2.5 Spatiotemporal Gait Parameters

The ANOVAs performed on the spatiotemporal gait variables revealed significant interactions of pack type and walking speed on stride time ($p = .048$), stance duration ($p = .043$), and swing duration ($p = .043$). These interactions are plotted in Figure 11. At the walking speed of 1.34 $m \cdot s^{-1}$, the stride times with the LP and the MOLLE were similar. Stride times for both packs were lower at the 1.61 $m \cdot s^{-1}$ speed, but the LP showed a greater decrease in stride time than the MOLLE (Figure 11). With the MOLLE, stance duration as a percentage of stride time was essentially the same for the two walking speeds. With the LP, however, stance duration was shorter at the 1.61 $m \cdot s^{-1}$ speed than it was at the speed of 1.34 $m \cdot s^{-1}$ (Figure 11). With regard to swing duration as a percentage of stride time, again the MOLLE values were essentially the same at the two walking speeds. With the LP, swing duration was longer at the 1.61 $m \cdot s^{-1}$ speed than it was at the speed of 1.34 $m \cdot s^{-1}$ (Figure 11). Table 25 contains the means and standard errors for all spatiotemporal measures. There were no significant main effects of pack type on any of the spatiotemporal gait variables.

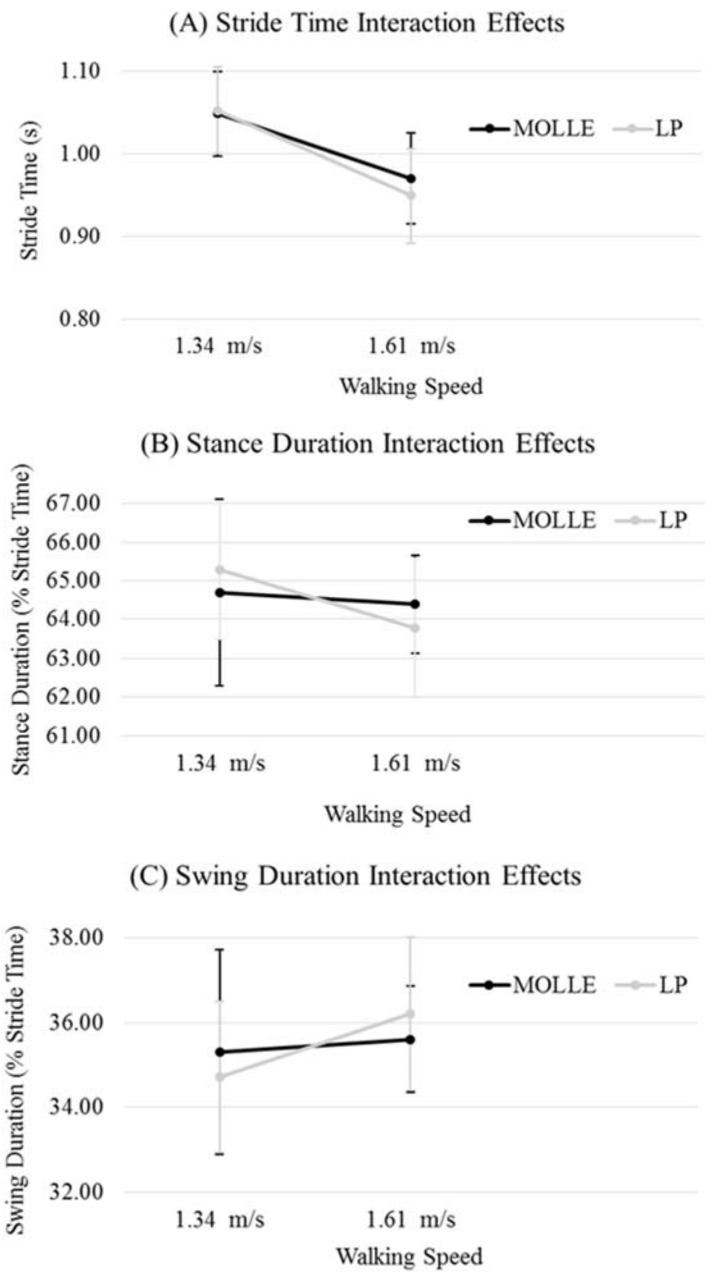


***Figure 11**: Mean values* (±1 *SD*) *for (A) stride time, (B) stance duration, and (C) swing duration for each pack type at the 1.34 and the 1.61 $m{\cdot}s^{-1}$ walking speeds on a 0% grade.*

Table 25: *Means (SE) of the spatiotemporal gait parameters for each pack type and walking speed on a 0% grade.*

Parameter	**Pack Type**		**Walking Speed (m·s^{-1})**	
	MOLLE	**LP**	**1.34**	**1.61**
Stride Length[a] **(m)**	0.99 (0.02)	0.98 (0.02)	1.03 (0.02)	0.94 (0.02)
Stride Width (m)	0.16 (0.01)	0.16 (0.01)	0.16 (0.01)	0.16 (0.01)
Stride Time[a,b] **(s)**	1.01 (0.02)	1.00 (0.02)	1.05 (0.02)	0.96 (0.02)
Stance Duration[a,b] **(% stride time)**	64.55 (0.50)	64.54 (0.51)	64.99 (0.59)	64.09 (0.43)
Swing Duration[a,b] **(% stride time)**	35.46 (0.48)	35.46 (0.51)	35.01 (0.59)	35.91 (0.43)
Double Support Duration (% stride time)	29.18 (1.00)	29.10 (1.04)	30.01 (1.20)	28.27 (0.87)

[a]Significant main effect of walking speed, $p < .05$ or better. [b]Significant pack type by walking speed interaction, $p < .05$ or better.

3.2.3 Metabolics

The means and standard errors for the metabolic variables are in Table 26. There was one significant interaction between pack type and walking speed in the analyses performed on the metabolic variables (Figure 12). The variable yielding a significant interaction was HR ($p = .0001$).

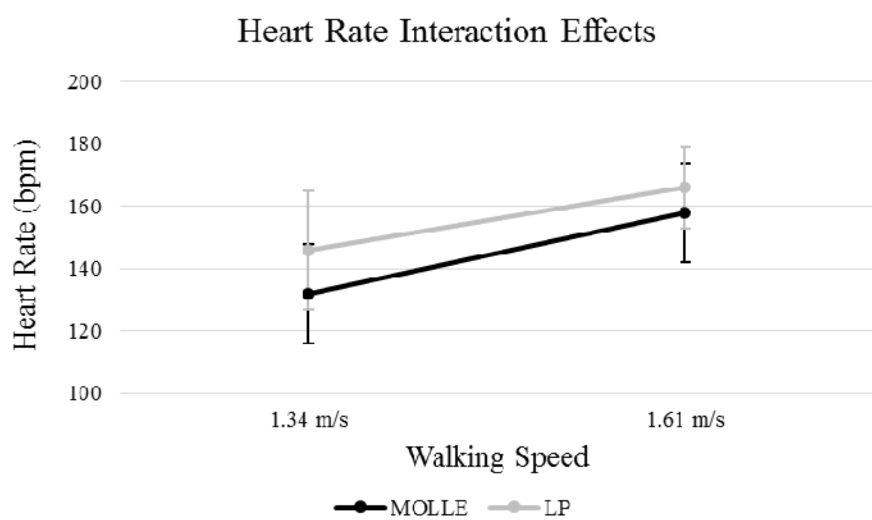


Figure 12: *Mean values (±1 SD) for heart rate for each pack type at the 1.34 and the 1.61 m·s-1 walking speeds on a 0% grade.*

There was also a significant main effect of pack type on $\dot{V}O_2$ expressed in absolute units ($p = .0001$), $\dot{V}O_2$ normalized to body weight ($p = .0001$), $\dot{V}O_2$ normalized to total weight ($p = .002$), R ($p = .015$), and HR ($p = .0001$). For each of these variables, the value for the LP was greater than the value for the MOLLE. For $\dot{V}O_2$ expressed in absolute units and $\dot{V}O_2$ normalized by body weight, the value for the LP exceeded that for the MOLLE by 10%. For $\dot{V}O_2$ normalized by total weight and for heart rate, the values for the LP exceeded the values for the MOLLE by 6% and 8%, respectively.

Table 26: *Means (SE) of the metabolic variables for each pack type and walking speed on a 0% grade.*

	Pack Type		**Walking Speed ($m \cdot s^{-1}$)**	
Parameter	**MOLLE**	**LP**	**1.34 m/s**	**1.61 m/s**
$\dot{V}O_2$[a,b] **($ml \cdot min^{-1}$)**	2423.60 (96.29)	2661.32 (70.37)	2227.74 (79.62)	2857.19 (87.75)
$\dot{V}O_2$ normalized to body weight[a,b] **($ml \cdot kg^{-1} \cdot min^{-1}$)**	29.06 (1.35)	31.85 (1.11)	26.68 (1.08)	34.23 (1.38)
$\dot{V}O_2$ normalized to total weight[a,b] **($ml \cdot kg^{-1} \cdot min^{-1}$)**	17.75 (0.73)	18.87 (0.59)	16.04 (0.60)	20.58 (0.72)
R[a,b]	0.88 (0.02)	0.91 (0.02)	0.86 (0.02)	0.93 (0.02)
HR[a,b,c] **(bpm)**	145.16 (4.45)	156.16 (4.38)	138.98 (4.99)	162.34 (4.11)
RPE[b]	10.63 (0.57)	11.38 (0.74)	9.67 (0.52)	12.33 (0.86)

[a]Significant main effect of pack type, $p < .05$ or better. [b]Significant main effect of walking speed, $p < .05$ or better. [c]Significant pack type by walking speed interaction, $p < .05$ or better.

3.2.4 LP Measurements

Table 27 presents the means and the standard errors of the power outputs of the LP, in Watts (W), at each of the two walking speeds with the grade set to 0%. For convenience, the equivalent energy is also presented, in Watt·hours (W·h), Joules (J), and kilocalories (kcal). Means and standard errors of the pack displacement at each speed are also presented in the table. There was a significant ($p < .0001$) main effect of walking speed on power output of the LP system. Walking at the 1.61 $m \cdot s^{-1}$ speed significantly increased power output of the LP system compared to walking at the 1.34 $m \cdot s^{-1}$ speed. Pack displacement was not significantly affected by walking speed.

Table 27: *Mean (SE) power and energy outputs and pack displacements of the LP for each walking speed on a 0% grade.*

	Walking Speed (m·s^{-1})	
Variable	**1.34**	**1.61**
Power (W)	5.56^{A} (1.70)	11.96^{B} (2.74)
Energy (W·h)	0.19 (0.06)	0.40 (0.09)
Energy (J)	688.20 (205.20)	1454.2 (329.60)
Energy (kcal)	0.16 (0.05)	0.35 (0.08)
Pack Displacement (m)	0.045^{A} (0.005)	0.055^{A} (0.005)

Note. Values that share a superscript with the same letter do not differ significantly from one another ($p > .05$). Values that do not share a superscript with the same letter differ significantly ($p < .05$ or better) from one another.

3.3 Agility Run

The results of the ANOVAs performed on the variables from the agility run are presented in Table 28. The table contains the means and standard errors for each pack condition and the significance levels (*p*-values) obtained in the ANOVAs. As shown in Table 28, there was a significant effect of pack condition on overall time to complete the course, as well as on three performance metrics analyzed at the turns: angular velocity about the vertical axis, normal acceleration, and anteroposterior (A-P) acceleration. There was no significant effect of pack condition on the other performance metrics examined (Table 28).

Table 28: *Means (SE) of dependent variables for the agility course task.*

VARIABLE	MOLLE	LP	*p*-value
Time to Complete (s)	11.72^{A} (0.11)	12.00^{B} (0.09)	0.002
Speed, horizontal (m·s^{-1})	1.49^{A} (0.08)	1.49^{A} (0.08)	0.954
Angular Velocity, vertical (rad·s^{-1})	1.78^{A} (0.04)	1.85^{B} (0.03)	0.014
Acceleration, tangential (m·s^{-2})	1.08^{A} (0.15)	0.98^{A} (0.11)	0.333
Acceleration, normal (m·s^{-2})	4.64^{A} (0.12)	4.35^{B} (0.11)	0.009
Acceleration, A-P (m·s^{-2})	0.82^{A} (0.12)	0.63^{B} (0.10)	0.033
Tilt, tangential (degrees)	18.67^{A} (2.78)	16.43^{A} (2.46)	0.484
Tilt, normal (degrees)	22.94^{A} (2.29)	19.57^{A} (1.15)	0.141
Tilt, A-P (degrees)	22.57^{A} (2.80)	18.12^{A} (2.52)	0.197

Note. Values that share a superscript with the same letter do not differ significantly from one another ($p > .05$). Values that do not share a superscript with the same letter differ significantly ($p < .05$ or better) from one another.

The time to complete the zigzag agility run was significantly longer when the LP was worn compared with the MOLLE (p = .002). Completion time was 0.28 s, or 2.4%, longer with the LP. The longer completion time with the LP may be a result of a shorter normal acceleration of 0.29 $m \cdot s^{-2}$ (p = .009) in combination with decreased A-P acceleration of 0.19 $m \cdot s^{-2}$ (p = .033) evident during the turns (Figure 13).

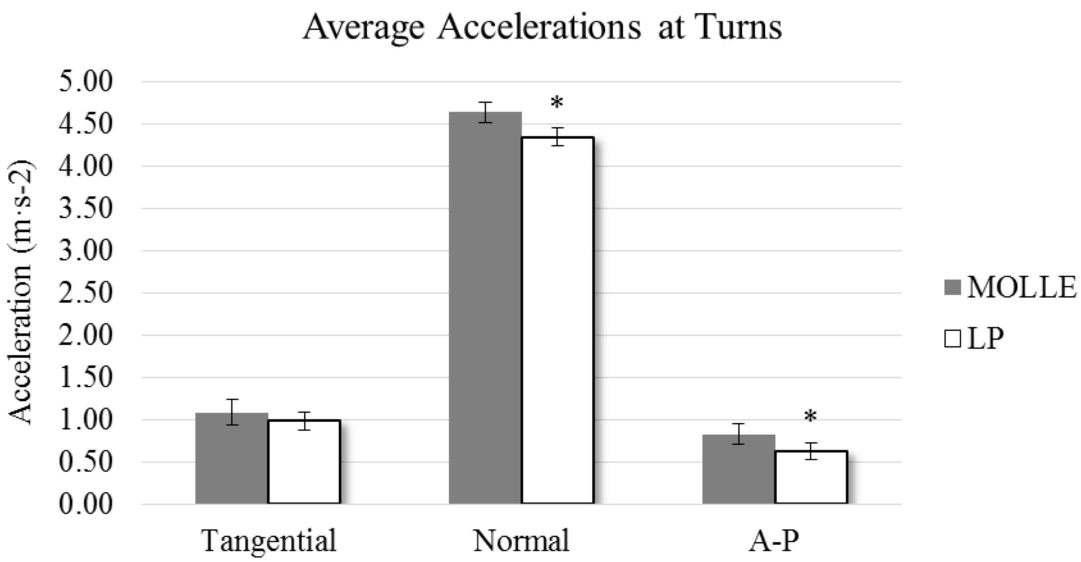


Figure 13: *Average sacral acceleration along the three examined axes (tangential, normal, and A-P). (*) Denotes a significant difference (p < .05 or better) between pack conditions.*

Participants also exhibited increased angular velocity about the vertical axis of 0.07 $rad \cdot s^{-1}$ (4.01 $deg \cdot s^{-1}$) with the LP compared with the MOLLE, indicating quicker rotation about the turns with the LP. This increase in angular velocity with the LP, occurring simultaneously with decreased linear accelerations, may illustrate a modified technique for navigating the turns with the LP. Despite these sacral angular velocity and linear acceleration differences, the remaining performance metrics, horizontal speed and sacral tilt in all three examined planes, did not differ significantly between pack conditions (p > .05; Figure 14).

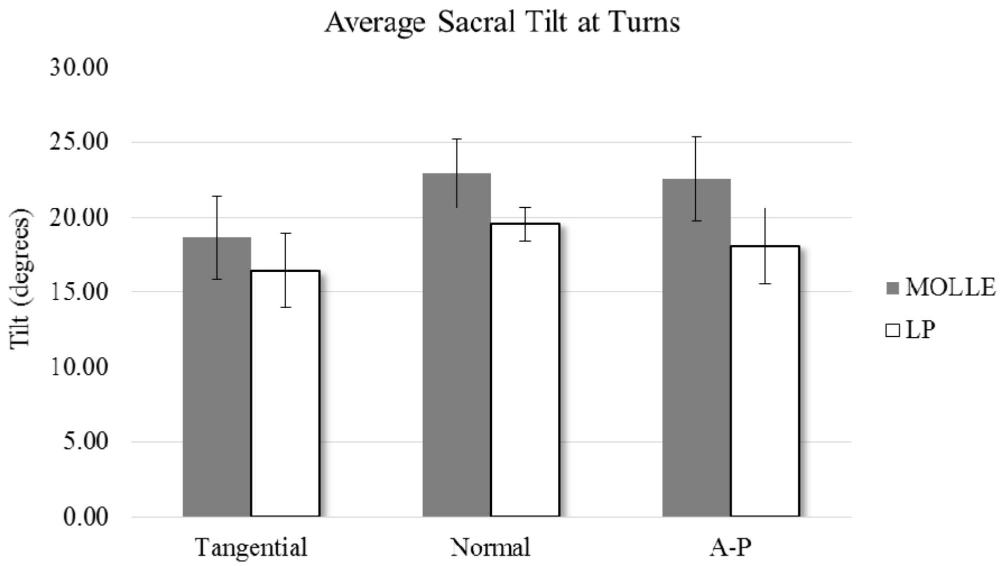


Figure 14: *Average sacral tilt angle within the three examined planes (tangential-vertical, normal-vertical, and A-P-vertical).*

4. DISCUSSION

4.1 Carrying the MOLLE and the LP Backpacks While Walking

4.1.1 Kinetics

In their study of an early prototype of the LP, Rome et al. (2005) found a reduction in the peak force exerted by the load on the load carrier during walking and jogging when the LP was in an unlocked position (i.e., pack free to oscillate on the frame), compared with the LP in a locked position. In general, lower peak forces transmitted to the body are considered a good characteristic in terms of minimizing injury risks to the load carrier (Knapik & Reynolds, 2012; Knapik et al., 2004). O'Donovan et al. (2015), in their small-scale study of the MOLLE large backpack and the LP prototype, examined GRF data for differences between the two backpacks in the forces to which the body was exposed during walking. Using a MOLLE and a LP that were loaded to an identical weight of 27 kg (60 lb), O'Donovan et al. (2015) found that 1st peak loading responses during walking were not consistently higher or lower with the LP than with the MOLLE. Further, vertical forces at mid-stance were higher with the LP for all three of their participants and 2nd peak vertical forces were lower with the LP than with the MOLLE for two of the participants.

The GRFs were again recorded in this evaluation. Given that the weight of the loaded LP exceeded the weight of the loaded MOLLE by 4.5 kg (9.9 lb), higher magnitude vertical peak forces would be expected with the LP (Birrell et al., 2007). The data acquired at a walking speed of 1.34 $m \cdot s^{-1}$ (3.0 $mi \cdot h^{-1}$) on 0%, 5%, and -5% grades and at walking speeds of 1.34 (3.0 $mi \cdot h^{-1}$) and 1.61 $m \cdot s^{-1}$ (3.6 $mi \cdot h^{-1}$) on a 0% grade indicated that, when normalized to body weight, 1st peak vertical force was consistently higher with the LP than with the MOLLE, although the difference was not statistically significant.

The GRF data acquired here were also normalized to total weight. Expressing the GRF data in this manner neutralizes the difference in backpack weights and allows examination of GRFs due to acceleration of the COM of the load-carrier-backpack system. Analyses of the normalized data acquired at a walking speed of 1.34 $m \cdot s^{-1}$ (3.0 $mi \cdot h^{-1}$) on the three grades and the data acquired at the two walking speeds on a 0% grade did not yield a significant difference between the MOLLE and the LP in 1st peak vertical force. Further, peak mid-stance vertical force was consistently higher with the LP, but not significantly so. Analysis of the data acquired at the two walking speeds did reveal a significant difference between the pack types for 2nd peak vertical force. On this measure, the force normalized to total mass was lower by 13% with the LP than with the MOLLE. Although the difference was not significant, 2nd peak vertical force was also about 8% lower with the LP for the data acquired at the three grades.

The GRF data normalized to total weight revealed other significant findings in the analyses of the two walking speeds. At 1.34 $m \cdot s^{-1}$ (3.0 $mi \cdot h^{-1}$), peak braking forces for the two pack types were essentially equal. At the walking speed of 1.61 $m \cdot s^{-1}$ (3.6 $mi \cdot h^{-1}$), peak braking forces were higher (more negative) for both packs, but the LP evidenced less of an increase than the MOLLE did. For both speeds, peak propulsive force and 2nd peak medial force were significantly lower with the LP than with the MOLLE.

Overall, the results for the GRFs normalized to total weight revealed that forces with the LP were not different from or were less than those with the MOLLE. The findings of lower magnitude forces with the LP appear to be in consonance with the findings of Rome et al. (2005) from their testing of an early LP prototype. Rome et al. (2005) measured force at the pack frame, not at the ground. The data acquired here on GRFs provide a more detailed picture, in three orthogonal directions, of the forces acting on the body throughout the stance phase of the gait cycle.

Of particular interest among the force-related variables normalized to total weight are the findings for 2nd peak vertical and peak propulsive forces. In the latter part of the stance period of walking, the body and the external load being borne must be propelled forward into the next step. To do this, the load carrier must raise the load against gravity, control the horizontal force components, and generate the force to move the body forward, all energy-intensive activities. In the analyses of walking speeds, 2nd peak vertical and peak propulsive forces normalized to total weight were lower with the LP than with the MOLLE, suggesting that push off into the next step might be degraded with the LP, resulting in the lower peak forces. It can be posited that the oscillation of the LP on the frame resulted in the lower 2nd peak vertical and peak propulsive forces. With the oscillations, the COM of the backpack can be expected to change somewhat over the stance period, perhaps making the backpack load more difficult to control. Although the particular design features of the LP that contributed to the lower vertical and propulsive forces late in the stance period cannot be positively identified, the likely outcome is that more energy would be needed to propel the body forward with the LP than with the MOLLE.

4.1.2 Kinematics

The kinematic data were analyzed to identify postural differences during wear of the MOLLE versus the LP. These data revealed that the principal differences between the packs were in the trunk and hip angles during walking. The data acquired at a walking speed of 1.34 $m \cdot s^{-1}$ (3.0 $mi \cdot h^{-1}$) on 0%, 5%, and -5% grades and at walking speeds of 1.34 (3.0 $mi \cdot h^{-1}$) and 1.61 $m \cdot s^{-1}$ (3.6 $mi \cdot h^{-1}$) on a 0% grade indicated greater forward lean of the trunk with the LP than with the MOLLE. Maximum and minimum trunk angles were significantly greater with the LP, and trunk ROM was significantly less with the LP, indicating greater forward lean of the trunk throughout the gait cycle. Related to the trunk angle findings, analyses of the data indicated that there was greater flexion of the hip with the LP than with the MOLLE. Both the analyses of grades and the analyses of walking speeds yielded significant differences between pack types in maximum and minimum hip angles.

Polcyn et al. (2002) reported that load weight is highly correlated (r = .80 or better) with the amount of forward trunk lean. They also reported a relatively high correlation between load weight and hip angle (r = .5 or better). Kinoshita (1985) proposed that the inclined posture facilitates forward propulsion of the body and load into the next step. It is possible that the differences between the packs in trunk and hip angles found here were attributable to the fact that the LP was heavier, by 4.5 kg (9.9 lb), than the MOLLE was. Relatedly, it can also be posited that, as Kinoshita (1985) proposed, the increased forward trunk lean with the LP was a means of augmenting forward propulsion of the body and the load. However, the differences in forward trunk lean between and LP and the MOLLE were large. In analysis of the grade data, it was found that trunk lean was 67% greater with the LP. Analysis of the data acquired at two speeds revealed that trunk lean was 44% greater with the LP. Therefore, it is possible that a factor, other than the weight difference between the two packs, contributed to the results. It may be that oscillation of the LP and associated dynamic changes in the backpack COM played a role.

In their testing of the early LP prototype, Rome et al. (2005) noted that there may be differences in walking gait with the LP in an unlocked configuration (i.e., free to oscillate on the frame), rather than in a locked position. They particularly cited the possibility that pack configuration affects the amount of work performed during the double support phase of the gait cycle. However, Rome et al. (2005) did not acquire data on gait variables. Spatiotemporal gait variables were analyzed in the current evaluation. Double support duration as a percentage of stride time was one of the variables examined. This variable was not significantly affected by pack type, but other spatiotemporal variables were.

Analyses of the data acquired during walking at 1.34 $m \cdot s^{-1}$ (3.0 $mi \cdot h^{-1}$) on 0%, 5%, and -5% grades did not reveal significant differences between packs for any of the gait variables. However, analyses of the data acquired at the 1.34 $m \cdot s^{-1}$ (3.0 $mi \cdot h^{-1}$) and the 1.61 $m \cdot s^{-1}$ (3.6 $mi \cdot h^{-1}$) speeds on a 0% grade did yield several interactions between speed and pack types that were significant. Thus, the two packs differed in the manner in which some spatiotemporal measures changed as walking speed changed. Stride time was one of the variables for which a significant interaction was found. At the lower speed, time to complete a stride was approximately equal for the two pack types, whereas time to complete a stride was shorter with the LP than with the MOLLE at the higher speed. The implication is that stride frequency, or the number of strides taken within a given time period, was higher with the LP than with the MOLLE at the 1.61 $m \cdot s^{-1}$ (3.6 $mi \cdot h^{-1}$) speed, but not at the speed of 1.34 $m \cdot s^{-1}$ (3.0 $mi \cdot h^{-1}$).

Stance duration and swing duration as percentages of stride time are related spatiotemporal variables and a significant interaction was obtained between pack type and walking speed for both variables. For the MOLLE, stance duration was approximately equal at the two walking speeds. This was also the case for swing duration with the MOLLE. For the LP, stance duration as a percentage of stride duration was shorter at the higher walking speed than at the lower walking speed. Similarly, swing duration as a percentage of stride duration was longer at the higher walking speed than at the lower walking speed.

From the findings for the gait variables at the two speeds, it appears that the LP affects gait differently than the MOLLE and that the impact of the LP on gait is speed dependent. Only two walking speeds were tested in this evaluation. Therefore, information on the speed-gait relationship with the LP is limited. However, it is likely that oscillation of the LP as affected by walking speed has some role in affecting spatiotemporal gait parameters.

4.1.3 Metabolics

The metabolic data collected in this evaluation revealed significant differences between the LP and the MOLLE in the energy cost of carrying the loads. Load weight is a large contributor to the metabolic cost of walking with a load (Obusek, Harman, Frykman, Palmer, & Bills, 1997; Patton, Kaszuba, Mello, & Reynolds, 1991; Polcyn et al., 2002). The weight of the LP is 4.5 kg (9.9 lb) greater than that of the MOLLE and equal payloads were placed in both packs for this evaluation. Therefore, the significantly greater values found for the LP compared with the MOLLE for $\dot{V}O_2$ and for $\dot{V}O_2$ normalized to body weight were expected. Other indicators of metabolic cost, including heart rate and respiratory quotient, were also significantly higher when walking with the LP system. Given the differences in weight between the two backpack systems, the observed differences in metabolic cost were expected.

However, when $\dot{V}O_2$ was normalized by total weight, the significant differences in oxygen consumption persisted. This was the case in the analyses of data acquired at a walking speed of 1.34 $m \cdot s^{-1}$ (3.0 $mi \cdot h^{-1}$) on 0%, 5%, and -5% grades and at walking speeds of 1.34 (3.0 $mi \cdot h^{-1}$) and 1.61 $m \cdot s^{-1}$ (3.6 $mi \cdot h^{-1}$) on a 0% grade. These findings indicate that, aside from straightforward differences in pack weight, walking with the LP is less metabolically efficient than walking with the MOLLE. There are several possible reasons for this. A possibility is that the vertical oscillation of the LP load on the back of the load carrier increases muscle activation in the trunk, increasing metabolic cost. The more extreme forward lean of the trunk while carrying the LP compared with the MOLLE could also result in increased muscle activation and increased metabolic cost. In addition, the lower 2nd peak vertical and propulsive forces with the LP may indicate that more energy was required to propel the body forward into the next step with the LP than with the MOLLE.

Another possibility focuses on the design of the LP system itself. Previous studies have shown that the location of the backpack COM is an important factor affecting the metabolic cost of load carriage. Obusek et al. (1997) demonstrated that load COMs high on the back and located anteriorly relative to the back (i.e., close to the load-carrier's back) are more metabolically efficient than loads carried in low, more posterior positions. Due to the need to have the LP load partially de-coupled from the body (to allow for oscillation and energy generation), the frame of the LP system is much deeper than the MOLLE frame. This means that, regardless of the height of the load COM, the load COM always sits more posterior to the body in the LP system. The heavier the load carried, the greater the impact this increased distance from the load-carrier's back will have. In addition, due to the oscillation of the load during periods of the gait cycle, the COM of the load will shift from a high location to one much lower on the load carrier's back. Though it will only remain in this position for a short period of the gait cycle, the necessity to control the force components of the load could be contributing to the increase in metabolic cost with the LP compared with the MOLLE.

4.2 Carrying the MOLLE and the LP Backpacks on the Maximal Effort Agility Run

Use of the LP system during the agility run did not demonstrate any performance advantages compared to the MOLLE system. On average, the total time to complete the five-cone agility course was 2.4% longer with the LP than with the MOLLE. The increase in time may be a result of the 0.29 $m \cdot s^{-2}$ decrease in normal acceleration in combination with decreased anteroposterior acceleration of 0.19 $m \cdot s^{-2}$ measured during the turns about the cones. Increasing the carried load has been shown to increase time to complete agility maneuvers on obstacle courses (O'Neal, Hornsby, & Kelleran, 2014). It is, therefore, possible that the heavier weight of the LP system compared with the weight of the MOLLE system was the main factor in decreasing performance on the agility task. There is the possibility, as well, that the oscillation of the LP during the rapid, dynamic movements of the agility run, together with the offset of the LP pack bag from the load-carrier's back, may have required greater effort by the load carrier to control the force components of the backpack, increasing completion time.

4.3 Lighting Pack Power Outputs

Results from the power output data collected from the LP system showed that, across walking speed and grade conditions, the LP system produced an average of 6 W of power. The LP system provided more power (11.96 W) during walking at 1.61 $m \cdot s^{-1}$ (3.6 $mi \cdot h^{-1}$) on the 0% treadmill grade than during walking on the 0% grade at the slower speed of 1.34 $m \cdot s^{-1}$ (3.0 $mi \cdot h^{-1}$). Pack displacement (5.50 cm) was greater at the higher speed as well, and did appear to be related to both the walking speed and the power output of the pack, as was expected.

The specific energy (also known as the energy density, in Joules per kg) of the LP, based on the average power output, is $1.3 \cdot 10^2 J \cdot kg^{-1}$. For reference, the specific energy of the standard-issue BB-2590/U battery is $4.6 \cdot 10^2 J \cdot kg^{-1}$. At a walking speed of 1.34 $m \cdot s^{-1}$ (3 $mi \cdot h^{-1}$) with a 27.2-kg (60-lb) load, it would take 34.5 h of continuous walking with the LP system to fully charge one BB-2590/U battery (assuming the battery starts completely drained). Given that there is estimated to be 12.6 h (±10 h) of tactical movement during a typical 72-h military mission (Draper Laboratory, 2014), and assuming the Soldier moves at 1.34 $m \cdot s^{-1}$ (3 $mi \cdot h^{-1}$) for the duration of the tactical movement, a LP system could charge one BB-2590/U battery to 37% during a 72-h mission.

A simplified assumption could then be made that, by using the LP system, a Soldier could “remove” 37% of one BB-2590/U battery and still maintain power requirements. This means the Soldier could remove 0.51 kg (1.13 lb) from the carried load. However, the addition of the LP system incurs a 4.5-kg (9.9-lb) penalty over the standard-issue MOLLE system. Therefore, for the addition of 4.5 kg (9.9 lb), a Soldier saves only 0.51 kg (1.13 lb).

When extended to the squad level, assuming all members of the squad are issued LP systems, this means that, for the addition of 40.8 kg (90 lb) to the squad, the squad saves only 4.63 kg (10.2 lb) in battery weight. Therefore, across the squad, for the addition of 40.8 kg (90 lb) of gear, the squad could carry approximately three fewer batteries out of the 29 batteries that are needed by a squad to complete a 72-h mission. The resulting net weight increase for the squad is 36.2 kg (79.8 lb).

Realistically, Soldiers will not maintain a constant speed of 1.34 $m \cdot s^{-1}$ (3 $mi \cdot h^{-1}$) for the duration of the 12.6 h of tactical movement. There will be changes in speed and short halts in movement. This will affect the power output of the LP system. It has been reported that, when considering distance traversed over an extended time, on average Soldiers moved at only 0.98 $m \cdot s^{-1}$ (2.2 $mi \cdot h^{-1}$) during tactical movements (Draper Laboratory, 2014). This speed may decrease the generation capabilities LP system. In addition, at this time only two squad positions (Squad Leader and Team Leader) carry power management hubs and, thus, only these positions would likely carry a LP system during tactical movements. These factors will reduce the total battery weight that could be removed from the squad.

Using data from an early prototype of the LP (Rome et al., 2005), Donelan et al. (2008) applied the COH formula (Equation 1) to obtain a value to reflect the efficiency of the LP as an energy harvesting device. A lower COH value indicates a lower cost for harvesting electrical power. Donelan et al. (2008) reported an expected COH of 12.9 and obtained an actual COH value of 4.8 ± 3.0 (mean ± SD). This was less than 40% of the expected value, indicating good efficiency of the early LP prototype. The exact device efficiency of the current LP prototype is unknown.

However, using the power output from the LP system recorded during the current evaluation and the corresponding change in metabolic power between the LP system (while harvesting energy) and the MOLLE system (no energy harvesting), an actual COH for the current system for each condition can be calculated. The values are presented in Table 29.

Table 29: *Measures for calculating COH for the LP system for each treadmill walking condition tested.*

Condition	LP Power Output (Watts)	LP Mean Metabolic Power (Watts)	MOLLE Mean Metabolic Power (Watts)	COH
0% grade, 1.34 $m \cdot s^{-1}$	5.56	820.98	733.99	15.7
5% grade, 1.34 $m \cdot s^{-1}$	6.82	1136.99	1047.14	16.2
-5% grade, 1.34 $m \cdot s^{-1}$	6.06	625.84	548.79	13.9
0% grade, 1.61 $m \cdot s^{-1}$	11.96	1036.62	957.69	14.2

All COH values reported in Table 29 are greater than both the expected and actual values of 12.9 and 4.8, respectively, from the early prototype (Donelan et al., 2008), indicating that the current prototype is less efficient than the early one at harvesting electrical power. The efficiency of the current LP prototype can be approximated from the COH equation (Equation 1). Doing so gives a device efficiency as follows: 25.5% for the 0% grade, 1.34 $m \cdot s^{-1}$ condition; 24.6% for the 5% grade, 1.34 $m \cdot s^{-1}$ condition; 28.7% for the -5% grade, 1.34 $m \cdot s^{-1}$ condition; and 28.1% for the 0% grade, 1.61 $m \cdot s^{-1}$ condition. Summarizing these data across all conditions tested in this evaluation, average efficiency for the current LP prototype is 27%.

4.4 Considerations in Developing Energy Harvesting Backpacks

When considering future military load-carrying systems, a number of performance characteristics can be cited as basic elements if an energy-harvesting backpack is to function successfully as carrying equipment for military loads and as an energy generator. Some of these are:

- The new system adds a critical capability that the current standard-issue system does not have.
- The new system generates a useful amount of power by either significantly extending mission duration or significantly reducing the Soldier (battery) load that must be carried.
- Injury risk factors are reduced with the new system, compared with carrying the equivalent payload in current Army load-carriage gear.
- Metabolic cost of load carriage with the new system is less than or equal to the metabolic cost of carrying the same payload in the equivalent Army standard-issue system.
- The new system significantly increases soldier mobility and agility over the standard issue system.
- The new system increases Soldier comfort over the standard-issue system.

Aspects of these characteristics were explored in the conduct of the current evaluation and information was obtained on how the prototype LP performed relative to desirable characteristics for an energy harvesting device that serves as a military backpack.

It is clear that the current LP prototype adds a capability that the standard-issue MOLLE does not possess. The ability to generate electrical power from the kinetic motion of human movement is beyond the scope of the MOLLE design. The definition of what is considered a "useful" amount of power for an energy harvesting device has not yet been determined. However, the power output data collected in this evaluation indicates that the current weight penalty of using the LP prototype overrides the benefit of the energy harvesting capability.

Injury risk factors in the context of the LP prototype were not explored. High magnitudes of GRFs have been implicated in the occurrence of overuse injuries of the lower extremities (Knapik & Reynolds, 2012; Knapik et al, 2004). The GRF data acquired in this evaluation did not indicate higher forces with the LP than with the MOLLE. Indeed, some of the forces were lower with the LP.

The metabolic data acquired in this evaluation with regard to use of the LP prototype as a military backpack indicates that, even when the heavier weight of the LP was accounted for, there was a metabolic penalty associated with carrying the LP compared with the MOLLE. Across grades and speeds, the LP system evidenced significantly lower metabolic efficiency than the MOLLE system.

The biomechanical data collected here suggest possible reasons for the increased metabolic cost. The vertical force at toe-off and the propulsive force were lower with the LP, indicating that the load carrier likely had to expend more energy to propel the body and the load forward during walking. Body posture was also different with the LP than with the MOLLE. This was particularly the case for the angle of the trunk. Forward lean of the trunk was much greater with the LP. The muscle activity entailed in maintaining this posture may have raised the energy cost of carrying the loaded LP.

Some differences between the LP prototype and the MOLLE were reflected in gait characteristics as affected by walking speed. The LP prototype showed changes that the MOLLE did not. It may be that the oscillation of the LP was affected by walking speed to the extent that basic parameters of walking gait were impacted. Only limited information on the speed-gait relationship with the LP was acquired here. However, it is likely that oscillation of the LP as affected by walking speed had some role in affecting spatiotemporal gait parameters.

Results from the agility run demonstrate that use of the LP significantly reduced Soldier performance on a maximal effort zigzag run compared with the MOLLE. It is possible that the oscillations of the LP and the offset of the LP pack bag from the load-carrier's back required greater effort for the load carrier to control the load, resulting in slower performance.

From their responses to the questionnaire administered by Hennessy (2015), it appears that participants in this evaluation preferred the MOLLE to the LP for overall comfort during load carrying. Participants' ratings indicated that they experienced more pressure and pain on the body with the LP than with the MOLLE and found load balance and stability to be better with the MOLLE than with the LP. It is possible that the participants' less positive responses to the LP were attributable to the fact that the weight of the LP was greater, by 4.5 kg (9.9 lb), than the weight of the MOLLE. However, it cannot be ruled out that participants' less positive responses to the LP were due to such characteristics of the LP as oscillation of the pack bag on the frame.

5. CONCLUSIONS AND RECOMMENDATIONS

The findings from this study indicate that carrying the LP prototype is less metabolically efficient than carrying the MOLLE. The LP affects the biomechanics of walking differently than the MOLLE, contributing to the higher metabolic cost. One element of the LP that might be affecting walking is the oscillation of the LP load, with the resultant dynamic changes in load COM versus body COM. It is also possible that the location of the load relative to the load-carrier's back causes changes in posture and GRFs that contribute to increased energy cost.

In terms of energy production during walking, the current weight penalty of using the LP prototype overrides the benefit of the energy harvesting capability the LP prototype.

Recommendations to improve performance of future LP prototypes based on the findings from the current evaluation are:

- Reduce the weight of the LP system
- Increase the efficiency of the LP to reduce the COH
- Reduce the depth of the LP frame design
- Design a study to test the effects of different oscillation frequencies on both power generation and gait mechanics. It is possible that tailoring the LP prototype oscillation frequency will isolate the effects of the LP on metabolic cost and walking biomechanics
- Recommendations for improved fit and comfort can be found in the report on the human factors questionnaire (Hennessy, 2015)

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APPENDIX A
Sample of the Borg Rating of Perceived Exertion Scale
(Reprint of original)

Volunteer Number:______ Date:________ Test Condition:___________

Borg Scale

RPE	**Exertion**
6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Instructions for Borg Rating of Perceived Exertion (RPE) Scale

While doing physical activity, we want you to rate your perception of exertion. This feeling should reflect how heavy and strenuous the exercise feels to you, combining all sensations and feelings of physical stress, effort, and fatigue. Do not concern yourself with any one factor such as leg pain or shortness of breath, but try to focus on your total feeling of exertion.

Look at the rating scale below while you are engaging in an activity; it ranges from 6 to 20, where 6 means "no exertion at all" and 20 means "maximal exertion." Choose the number from below that best describes your level of exertion. This will give you a good idea of the intensity level of your activity, and you can use this information to speed up or slow down your movements to reach your desired range.

Try to appraise your feeling of exertion as honestly as possible, without thinking about what the actual physical load is. Your own feeling of effort and exertion is important, not how it compares to other people's. Look at the scales and the expressions and then give a number.

9 corresponds to "very light" exercise. For a healthy person, it is like walking slowly at his or her own pace for some minutes

13 on the scale is "somewhat hard" exercise, but it still feels OK to continue.

17 "very hard" is very strenuous. A healthy person can still go on, but he or she really has to push him- or herself. It feels very heavy, and the person is very tired.

19 on the scale is an extremely strenuous exercise level. For most people this is the most strenuous exercise they have ever experienced.

Borg RPE scale

APPENDIX B
Time Series Plots of Select Variables at Three Grades

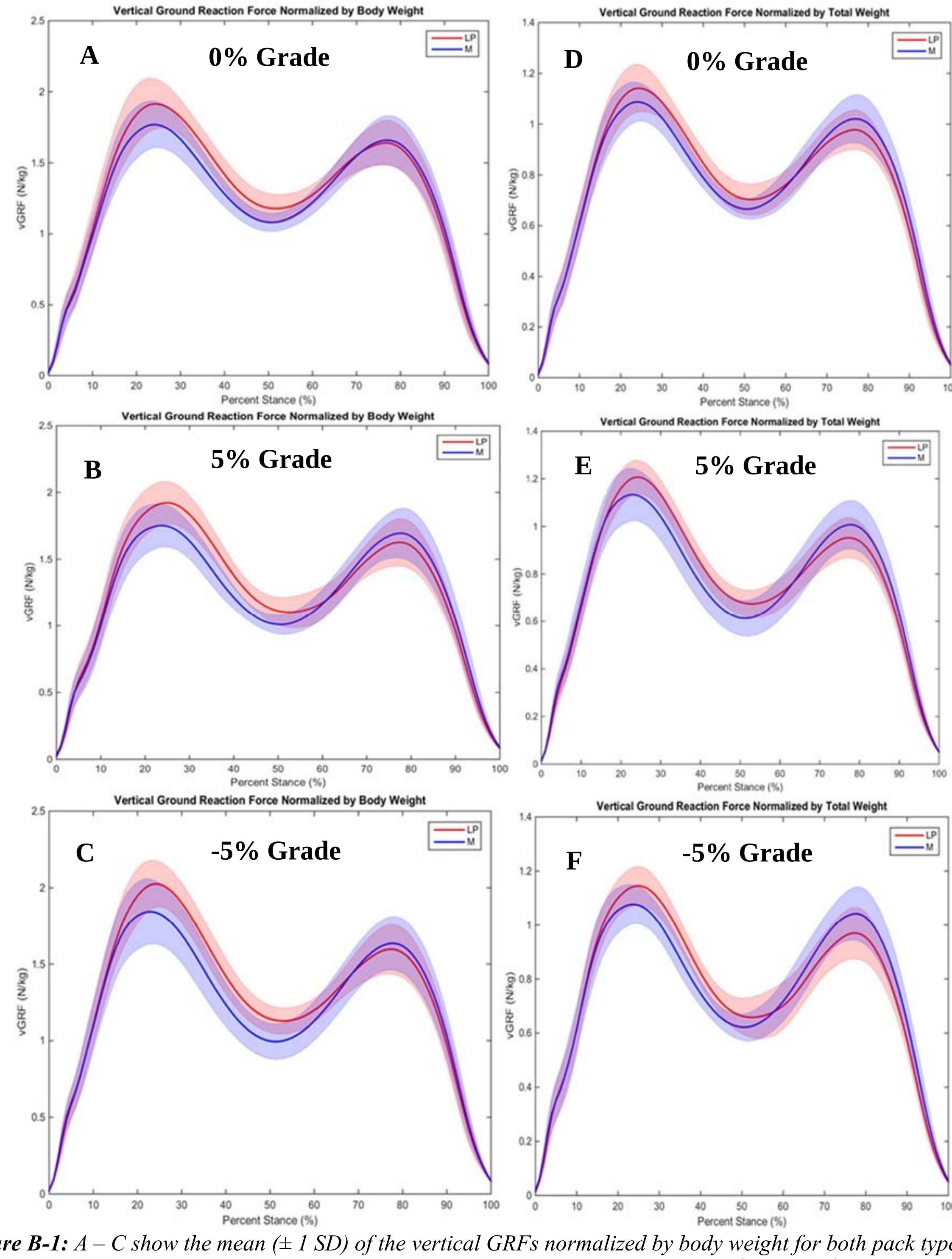

Figure B-1: *A – C show the mean (± 1 SD) of the vertical GRFs normalized by body weight for both pack types at the 0%, 5%, and -5% treadmill grades, respectively, with a walking speed of 1.34 $m{\cdot}s^{-1}$ (3.0 $m{\cdot}h^{-1}$). D – F show the mean (± 1 SD) of the vertical GRFs normalized by total weight for both pack types at the 0%, 5%, and -5% treadmill grades, respectively, with a walking speed of 1.34 $m{\cdot}s^{-1}$ (3.0 $m{\cdot}h^{-1}$).*

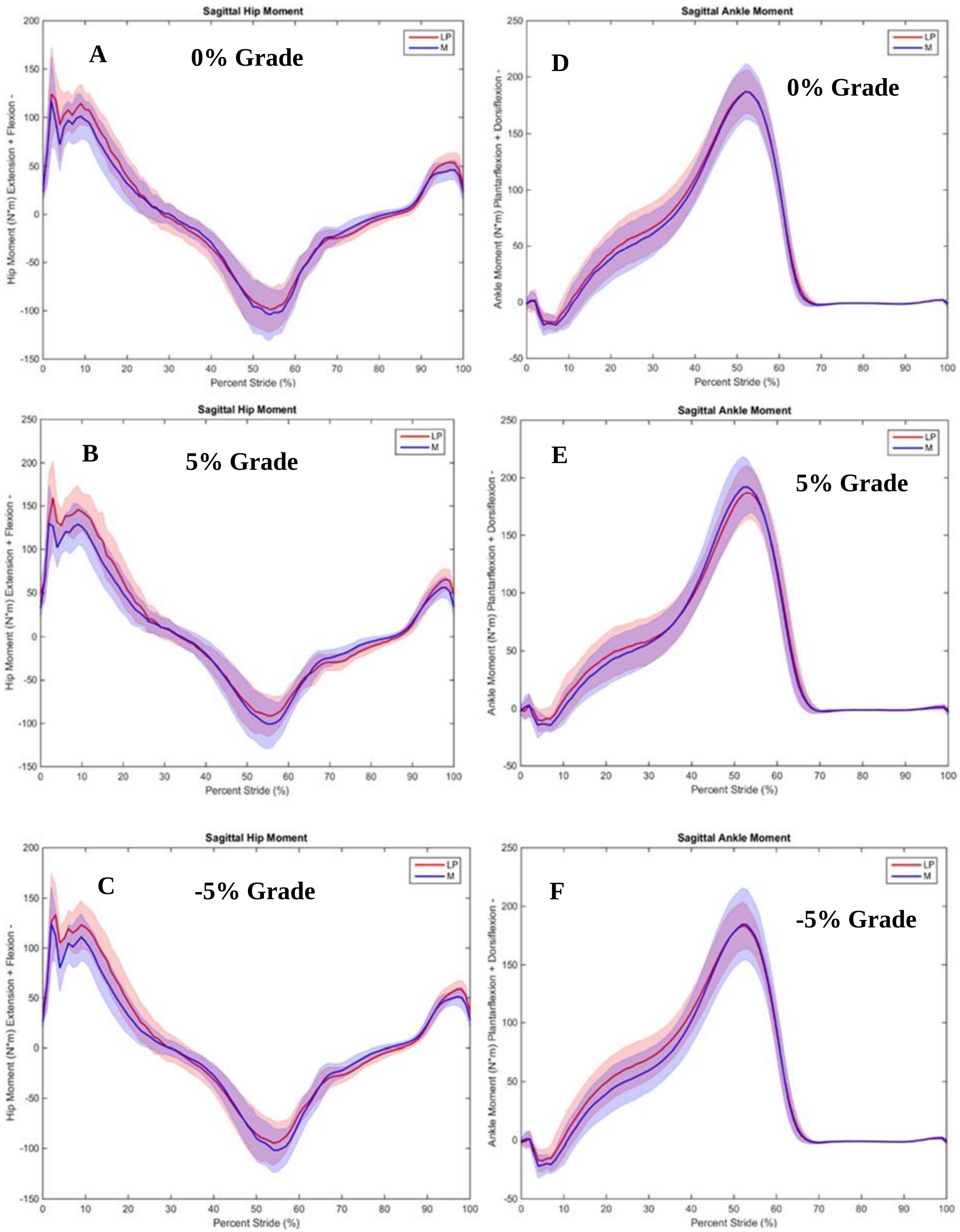

Figure B-2: *A – C show the means (±1 SD) of the sagittal hip moment for both pack types at the 0%, 5%, and -5% treadmill grades, respectively, with a walking speed of 1.34* $m \cdot s^{-1}$ *(3.0* $m \cdot h^{-1}$*). D – F show the means (±1 SD) of the sagittal ankle moment for both pack types at the 0%, 5%, and -5% treadmill grades, respectively, with a walking speed of 1.34* $m \cdot s^{-1}$ *(3.0* $m \cdot h^{-1}$*). There was a significant main effect of pack type on maximum hip moment (p = .004) and minimum ankle moment (p = .015)*

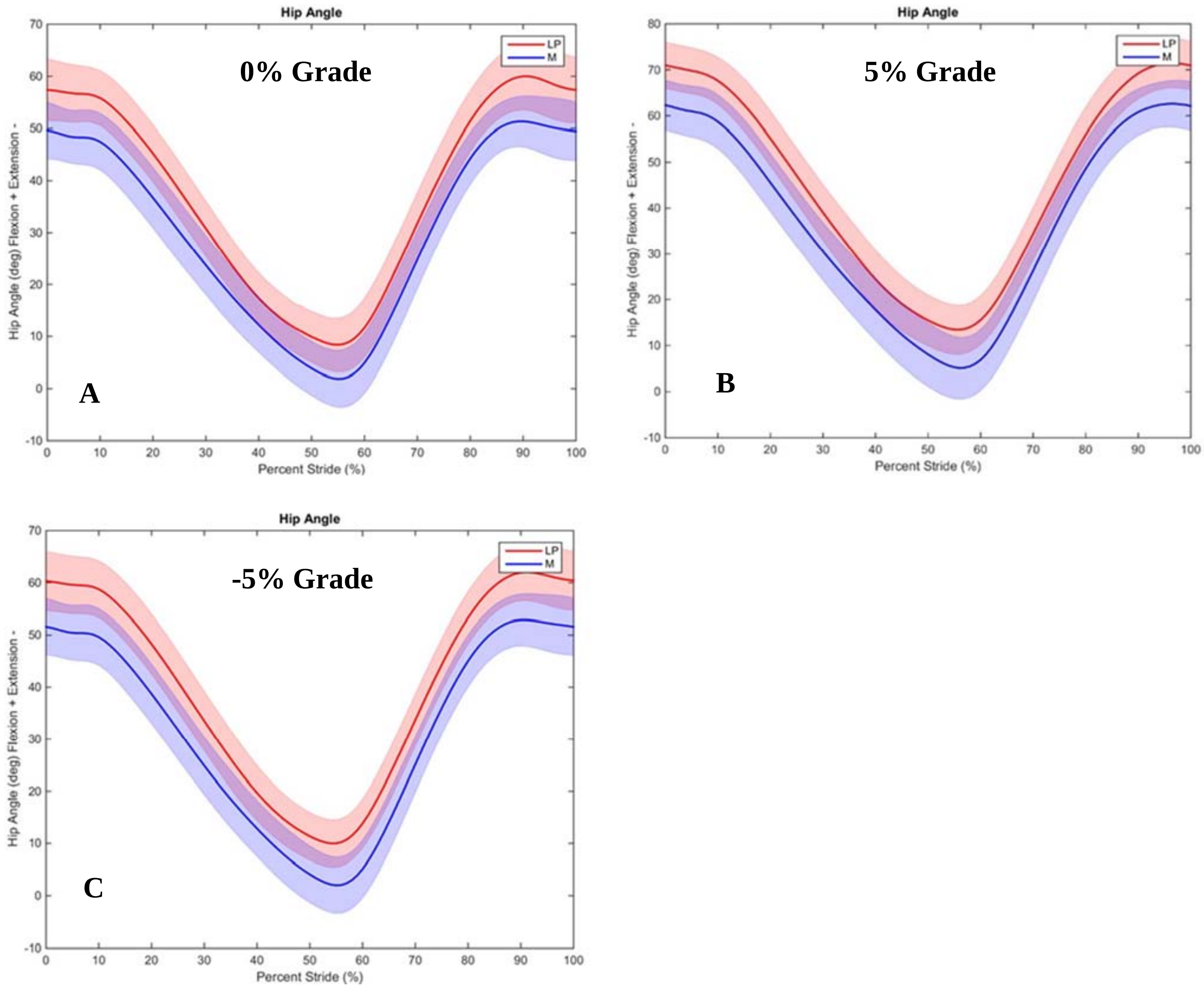

Figure B-3: *A – C show the mean (±1 SD) hip angle for both pack types at the 0%, 5%, and -5% treadmill grades, respectively, with a walking speed of 1.34* $m \cdot s^{-1}$ *(3.0* $m \cdot h^{-1}$*). Walking with the LP significantly increased maximum hip angle (hip flexion) and minimum hip angle (hip extension) when compared to walking with the MOLLE. There was no significant effect of pack type on hip ROM.*

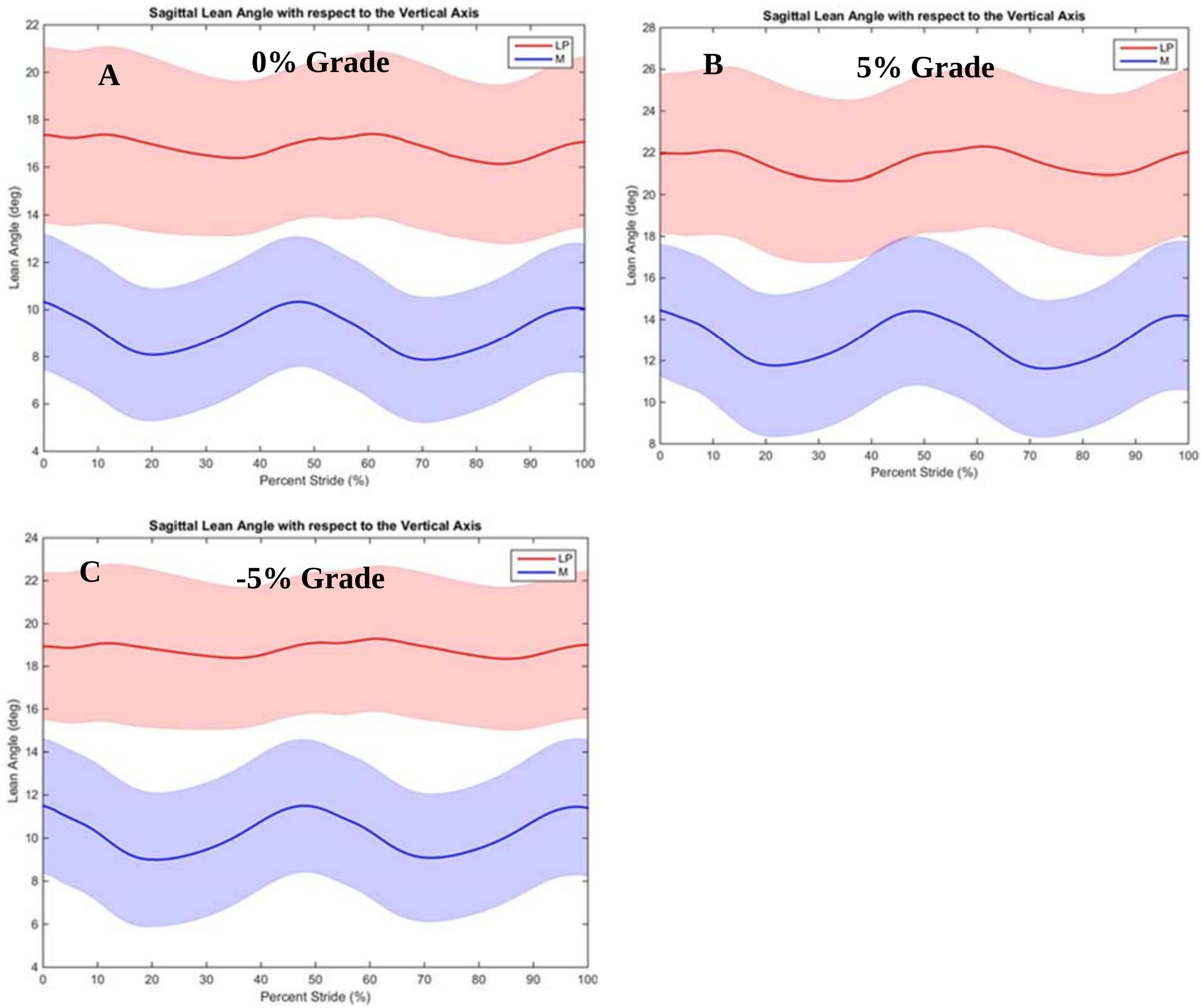

Figure B-4: *A-C show the mean (±1 SD) trunk lean angle for both pack types at the 0%, 5%, and -5% treadmill grades, respectively, with a walking speed of 1.34* $m \cdot s^{-1}$ *(3.0* $m \cdot h^{-1}$*). There was a significant effect of pack type on both the minimum trunk angle (*$p < .0001$*) and the trunk ROM (*$p = .013$*).*

APPENDIX C
Time Series Plots of Select Variables at Two Walking Speeds

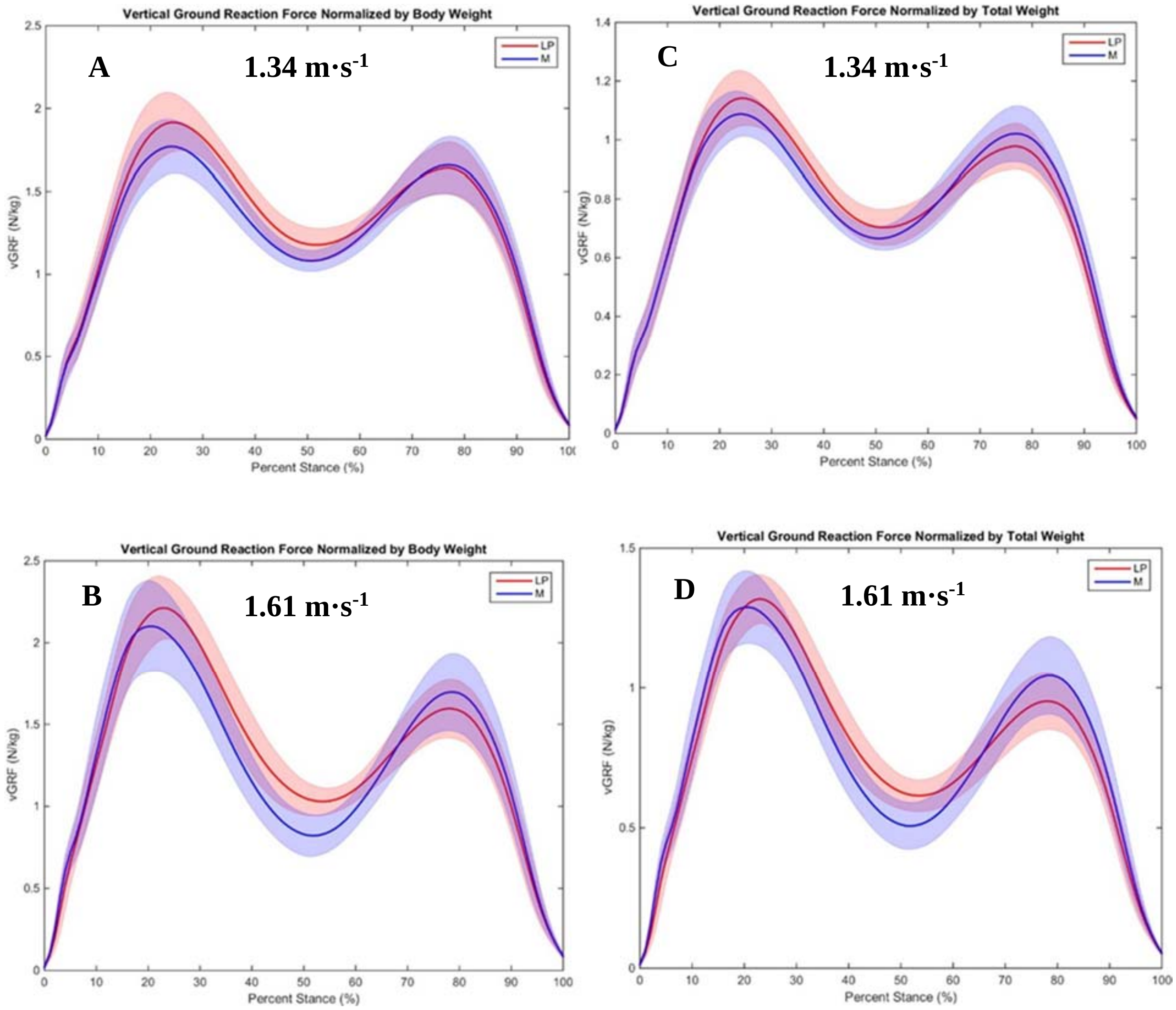

Figure C-1: *A – B show the mean (±1 SD) of the vertical GRFs normalized to body weight for both pack types at the 1.34 and 1.61 m·s^{-1} walking speeds, respectively, on a 0% grade. C – D show the mean (±1 SD) of the vertical GRFs normalized to total weight for both pack types at the 1.34 and 1.61 m·s^{-1} walking speeds, respectively, on a 0% grade.*

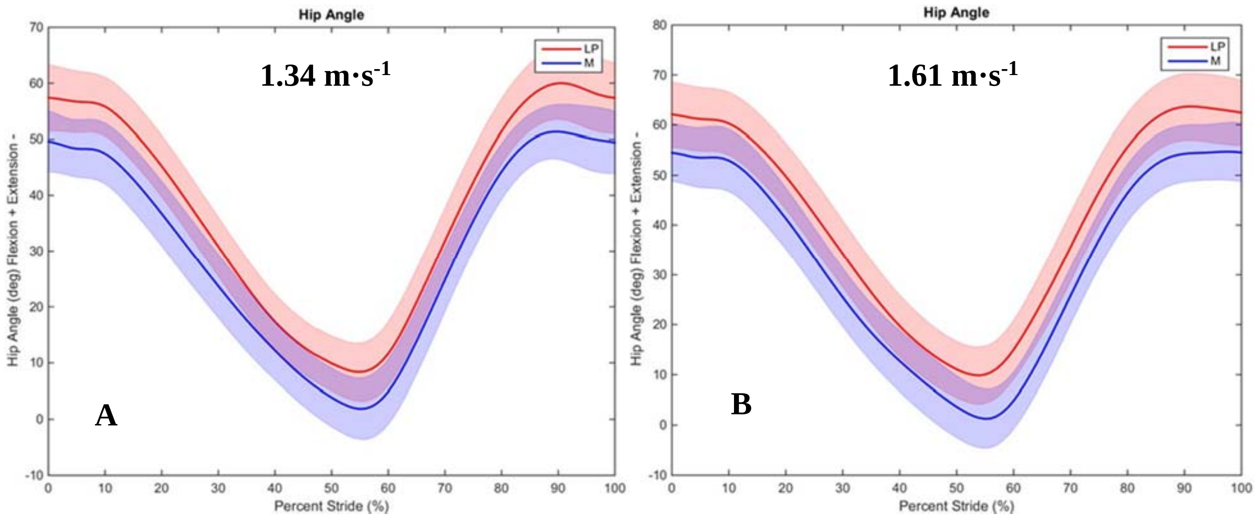

Figure C-2: *Mean (±1 SD) hip angle for both pack types at the (A) 1.34 and (B) 1.61 m·s^{-1} walking speeds on a 0% grade. Walking with the LP system significantly increased maximum hip angle (p < .0001), minimum hip angle (p < .0001), and hip ROM (p = .040) compared with the MOLLE.*

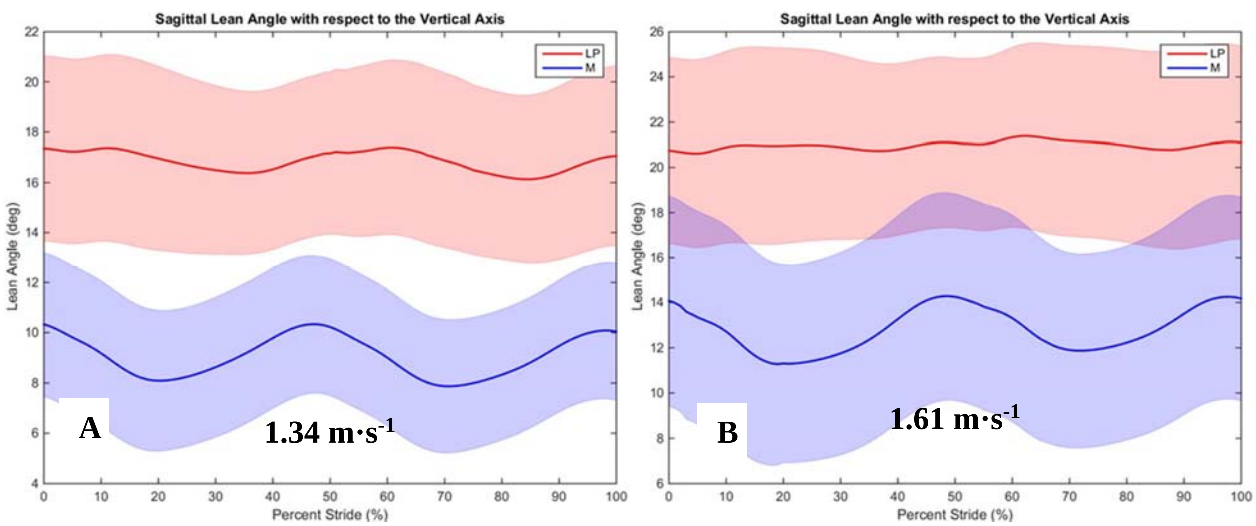

Figure C-3: *Mean (±1 SD) trunk lean angle for both pack types at the (A) 1.34 and (B) 1.61 m·s^{-1} walking speeds on a 0% grade. Walking with the LP system significantly increased the minimum trunk angle (p < .0001) and the maximum trunk angle (p <.0001). There was no significant effect of pack type on trunk ROM.*