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Spatiotemporal and kinematic changes in gait while carrying an energy harvesting assault pack system

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ABSTRACT

Soldiers are fielded with a variety of equipment including battery powered electronic devices. An energy harvesting assault pack (EHAP) was developed to provide a power source to recharge batteries and reduce the quantity and load of extra batteries carried into the field. Little is known about the biomechanical implications of carrying a suspended-load energy harvesting system compared to the military standard assault pack (AP). Therefore, the goal of this study was to determine the impact of pack type and load magnitude on spatiotemporal and kinematic parameters while walking at 1.34 m/s on an instrumented treadmill at decline, level, and incline grades. There was greater forward trunk lean while carrying the EHAP and the heavy load (decline: $p < 0.001$; level: $p = 0.009$; incline: $p = 0.003$). As load increased from light to heavy, double support stance time was longer (decline: $p = 0.012$; level: $p < 0.001$; incline: $p < 0.001$), strides were shorter (incline: $p = 0.013$), and knee flexion angle at heel strike was greater (decline: $p = 0.033$; level: $p = 0.035$; incline: $p = 0.005$). When carrying the EHAP, strides (decline: $p = 0.007$) and double support stance time (incline: $p = 0.006$) was longer, the knee was more flexed at heel strike (level: $p = 0.014$; incline: $p < 0.001$) and there was a smaller change in knee flexion during weight acceptance (decline: $p = 0.0013$; level: $p = 0.007$; incline: $p = 0.0014$). Carrying the EHAP elicits changes to gait biomechanics compared to carrying the standard AP. Understanding how load-suspension systems influence loaded gait biomechanics are warranted before transitioning these systems into military or recreational environments.

1. Introduction

Load carriage is an essential aspect of the military for survivability and execution of missions, although Soldiers carry loads often exceeding 40% of body mass (Koerhuis et al., 2009). Loads of at least 26 kg reduce combat effectiveness during periods of sustained military operations (Porter, 1992). Heavy posterior load induces greater forward trunk lean to counterbalance the change in center of mass, which leads to greater muscle strain in the shoulders and lower back (Attwells et al., 2006; Harman et al., 2000). Heavy loads also induce shorter strides to reduce stress on the body and increase stability (Birrell and Haslam, 2009; Espy et al., 2010; Kinoshita, 1985). Greater knee flexion has also been observed with increased load to serve as a shock absorber by mitigating the transfer of high impact forces from the body to the ground (Birrell and Haslam, 2009; Kinoshita, 1985). Although these gait adaptations are a natural response to maintain stability and counterbalance added mass, heavy loads elicit greater trunk lean and lower extremity flexion. These adaptations may limit Soldier mobility and readiness (Bonsignore, 2006) by restricting range of motion during tactical movement and inducing fatigue more quickly thereby negatively impacting readiness.

As technology progresses, Soldiers are required to carry more equipment for operational advantage. Consequentially, additional electronics require more batteries which increases the load on an already overburdened Soldier and could increase physical stress and risk of injury. A suspended-load backpack is an alternative load carriage system with mechanical or elastic components that permits vertical oscillation of a load in response to movement. Suspended-load systems reduce peak forces and metabolic cost during locomotion, which can lead to potential energy savings with increasing load (Rome et al., 2005; Xu et al., 2009). Some suspended-load systems incorporate a power generator that facilitates the conversion of mechanical energy from suspended-load

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vertical oscillation while walking (Rome et al., 2005; Xu et al., 2009). Energy harvesting technologies offer an alternative solution to carrying additional batteries by providing power generation during field operations. Hardware components are a necessary part of the design to afford energy conversion, but these components may restrict the dynamic movement of the Soldier.

An energy harvesting suspended-load system, the Energy Harvesting Assault Pack (EHAP), was developed to enable the Soldier to complete a mission without the need for carrying extra batteries. The EHAP mounts the standard Army assault pack (AP) on a custom suspended-load frame system that converts vertical kinetic energy into electrical energy. The purpose of this study was to examine the effects of pack and load on gait biomechanics. When carrying the heavy load and the EHAP, we hypothesized that users would exhibit shorter strides, longer double support stance time, greater knee flexion, and greater forward trunk lean. At level and incline grades, we anticipate no differences in stride length and double limb support time between AP and EHAP, but greater knee flexion and forward trunk lean when carrying the EHAP. At decline grade, we anticipate carrying the EHAP will result in longer strides, shorter double limb support time, greater trunk extension, and greater knee flexion. It is critical to evaluate implications of energy harvesting suspended-load systems on user biomechanics as significant changes could negatively impact operational performance.

2. Methods

2.1. Participants

Fifteen civilians (11 males; 28.3 ± 4.6 yrs.; 173.0 ± 9.7 cm; 74.6 ± 13.8 kg) volunteered to participate. All participants were healthy and engaged in at least 30 min of physical activity three days a week. Exclusion criteria included (1) current injury or pain in the lower extremities, neck, back, or shoulders, (2) prior joint surgery within the last year, (3) medical restrictions against aerobic exertion, high-impact activity, or load carriage, (4) neuropathy in the legs, (5) dizziness or vertigo, (6) having any medical condition or be taking medication known to affect balance. Prior to testing, volunteers provided written and verbal consent for participation. This protocol was approved by the Institutional Review Board of the U. S. Army Research Laboratory.

2.2. Procedures

Participants completed two data collection sessions separated by at least 48 h to avoid potential carryover of fatigue or muscle soreness. During each session, participants carried the AP and EHAP with the same load: 7.9 kg (light) or 15.9 kg (heavy). Due to the frame and hardware components of the EHAP, there is a mass difference between the empty AP (1.8 kg) and EHAP (6.8 kg). Therefore, the total masses carried by participants were as follows: (1) 9.8 kg for AP with light load, (2) 17.7 kg for AP with heavy load, (3) 14.7 kg for EHAP with light load, and (4) 22.7 kg for EHAP with heavy load.

Participants walked on an instrumented treadmill (ITM) (Advanced Mechanical Technology, Inc., Watertown, MA) at decline (−5%), level (0%), and incline (+5%) grades. For each pack-load-grade condition, participants walked for 5 min at 1.34 m/s (Fellin et al., 2016; James et al., 2015). This is a realistic pace Soldiers carry loads and pilot testing suggested this speed could be maintained at all conditions. At least 15 min of rest was provided following the completion of each pack-load-grade condition. For each session, participants were assigned to carry one load for the duration of the session. Within a session, participants completed testing with one pack first and then completed testing with the second pack. The order in which the packs were carried for the first session was counterbalanced among participants. For safety, testing at level grade was completed first. The order in which incline and decline grades were completed during the first session was counterbalanced among participants. For the second session, participants repeated testing procedures with the same pack and grade sequences for the second load.

2.3. Data analysis

Kinematic and kinetic data were recorded simultaneously at 120 Hz and 1200 Hz, respectively. Kinematic data were low-pass filtered at 6 Hz and kinetic data at 20 Hz using a fourth-order Butterworth filter. Reflective markers were placed on participants to collect kinematic data while walking on the ITM via 12-camera motion capture system (Motion Analysis Corp., Santa Rosa, CA). Additional markers were fixed to the posterior face of both packs, the EHAP frame and rigid components (Fig. 1). Ground reaction forces (GRFs) were collected from the ITM and normalized to each participant's body mass (N/BM). Outcome variables were processed and calculated using customized kinematic models and pipelines via Visual3D (C-Motion, Inc., Germantown, MD).

Outcome variables included: stride length (SL), double support stance time (DST), trunk lean (TL), and sagittal plane knee angle at heel strike (KA_{HS}) and range of motion during weight acceptance phase (KA_{WA}). Flexion angles were analyzed as positive values. Descriptions and calculations of outcome variables are presented in Table 1. During each pack-load-grade condition, data were collected for 20-s intervals at the 3, 3.5, and 4-min marks (each interval representing a single trial). Spatiotemporal variables were calculated for each gait cycle during a trial then averaged across the trial for a trial mean. Sagittal plane knee angles were calculated at each event (i.e. heel strike) and phase (i.e. weight acceptance) of a trial then averaged for a trial mean. Average trunk lean was calculated for each trial. Means from each of the three trials were averaged for a pack-load-grade condition mean and used for analyses.

2.4. Statistical analysis

All statistical analyses were performed using SPSS v22.0 software (SPSS Inc., Chicago, IL) with an alpha level set a priori at $p \leq 0.05$. Paired t-tests were performed to compare right and left limb means for all outcome variables. A 2 (pack) × 2 (load) repeated measures ANOVA was performed for all outcome

Fig. 1. Reflective markers were placed on the EHAP rigid and oscillating frame (left) to track vertical movement of the pack relative to the frame. Reflective markers were also placed on the face of the EHAP (left) and the standard assault pack (right).