The Effect of Carrying a Military Backpack on a Transverse Slope and Sand Surface on Lower Limb Kinetics

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Abstract

The objective of this study was to understand gait kinetics while walking on a sand surface (vs. hard surface) with wearing a traditional military ALICE backpack (vs. modularized MOLLE backpack). Twenty healthy male students participated in this study. Each participant completed a total of 72 trials (3 good trials for each testing configuration). These testing conditions were combinations of two surface types (hard, sand), two transverse slopes (flat, 10°), two walking speeds (self-selected, 4 km/h), and three load conditions (no load, MOLLE, ALICE). Walking on sand surface required a greater medial-lateral ground reaction force and a greater maximum vertical impact force. Hard surface gait resulted in a greater maximum vertical thrust force, a greater maximum braking force, and a greater maximum propulsive force. In terms of backpack effect comparison, mean hip abduction/adduction moment was greater while wearing the ALICE than the MOLLE. These results suggest that walking on sand with a backpack may increase the potential for injuries from overuse and falls. Hard surface walking on the other hand may increase the risk of foot strain and foot blisters.

Keywords: Military backpack, Sand surface, Transverse slope

Introduction

The U.S. military guideline suggests that the recommended weights of backpacks for prolonged ground operations should not exceed 33kg for an approach march [1]. The actual weights carried by ground troops, however, may vary depending on the components of the backpack [1]. On one hand the load carriage system should be optimized/lightened to increase soldier mobility and performance; on the other hand, certain components of the carrying load are critical for soldier survivability. Regardless, heavy load carriage systems can lead to reduced performance, injuries, and lack of readiness to fight [1-4]. In an effort to improve load carriage systems, research has been performed to determine how the weight of the load carried by a soldier affects their performance [2,5-12] and contributes to injuries [3,4,13].

The study of military load carriage on ground reaction force (GRF) provides important information on understanding gait mechanisms and therefore, is useful for the prevention of lower extremity injuries [10,14]. Previous research agrees that vertical GRF is directly related to the applied load [7,9,10,14,15]. Increased vertical forces at heel strike are a major risk factor for overuse injuries, such as stress fractures of the tibia and metatarsals, and knee joint problems. Increased anterior-posterior GRFs were also measured as load increased [7,10,15].

Another important factor that is related to GRFs is joint moments [7,16]. Stefanyszyn, et al (2006) proposed that high patellofemoral pain have resulted from higher knee abduction moment [17-19]. Increased knee abduction moments lead to increased lateral stress on the knee [20]. Increased stress is likely the reflection of increased load on the lateral facet of the patella [21]. Joint alignment and loading increases joint contact stress and may contribute to development of knee osteoarthritis. [22]

Uneven terrains are another factor of injuries [23]. Two common uneven terrains in current military operations are sand in Iraq and mountains in Afghanistan. There has been little, if any, research dealing with the lower extremity biomechanics for participants carrying backpacks on sand or rocks [24,25]. Increasing numbers of military personnel performing operations on uneven surface conditions provides greater motivation to conduct research on uneven surfaces.

The objective of this study was to expand the knowledge in this area by investigating kinetic parameters of gait on a sand surface while encumbered with a backpack. In addition, the gait kinetics of slanted surfaces was compared to those of flat surfaces. For the present study, several parameters were considered including ground reaction forces, joint moment and braking/propulsive forces.

Mtehod

Participants

Twenty male participants were recruited among students from the University of Utah (age 25.1 ± 3.6 years, height 175.6 ± 4.6 cm, weight 74.9 ± 7.7 kg). All participants met the current military anthropometric selection criteria (age 18 - 30, height 161 - 195 cm, weight 55 - 87 kg) [26]. Participants reviewed and signed an informed consent document approved by University of Utah Institutional Review Board.
Equipment

Two currently used military backpacks were selected (Figure 1). The ALICE (All-purpose Lightweight Individual Carrying Equipment) backpack is a military issue backpack consisting of a sack, aluminium frame, and various straps and supports. The MOLLE (Modular Lightweight Load-carrying Equipment) backpack is modularized with compatible pouches and accessories. The backpacks were slightly modified to install load cells in the straps and its total weight is 29 kg (64 lbs) each. This weight includes initial backpack weight, all associated accessories, and other devices for data collection. The University of Utah Military Science department provided the US Army issued desert tan BELLEVILLE 790G Gore-Tex combat boots.

![Figure 1. MOLLE (left) and ALICE (right) backpacks](image)

Two customized tracks were used to represent a sand surface and a hard surface respectively (Figure 2). Each track had the ability to increase the transverse slope to 10°. The length of each track was 7.3 m (24 ft). Two force plates (OR6-5-1000 & OR6-7, AMTI, Watertown, MA) were embedded and secured under the sand at the center of the track. Two other force plates (FP4060-08-1000, BERTEC, Columbus, OH) were used for the hard surface. They all collected ground reaction force data at a sampling rate of 1000 Hz. On the sand surface, specially designed isolation fixtures, designed for a previous study, were used to isolate sand over the force plate from the surrounding sand in the walkway [25].

![Figure 2. Two Tracks: Sand (left) and Hard (right)](image)

Motion data were captured using 16 NaturalPoint cameras (V100:R2) and AMASS software at a sampling rate of 100 Hz. Vicon Nexus (Vicon) was used for post processing and gap filling. Visual3D (C-Motion Inc.) software was used for additional processing and modelling.

![Figure 3. Dynamic Marker Set](image)

Experimental Protocol

Each participant completed a total of 72 trials (3 good trials for each testing configuration). These conditions were two surface types (hard, sand), two transverse slopes (0° vs. 10°), two walking speeds (self-selected, 4 km/h), and three load conditions (no load, MOLLE, ALICE). Transverse slope of 10° can be achieved by raising one side of the track using hand cranks installed on the track (Figure 3). Motion data was only recorded in one direction where the left foot was always upslope (UP) and the right foot was always downslope (DN) on the track. Self-selected speed was chosen by the participant as the representation of their normal walking speed. The 4 km/h speed was selected since it is the standard military marching speed of the U.S. Army [1]. Participants were instructed to follow a flag that was moving constantly along the walkway at a speed of 4 km/h. Once surface and slope were selected, all necessary trials were performed for that condition (randomized block design).

Data Analysis

The performance of the proposed model was evaluated using traditional biomechanics and statistical techniques. Key kinetic variables of gait analysis for this study were ground reaction forces (GRF) and moments. Each gait cycle generally had two vertical peak forces that could be measured after HS (heel strike) and before TO (toe off). The first vertical peak force was defined as impact force and the second vertical peak force was defined as thrust force. Maximum braking/propulsive forces, which could be measured anterior/posterior directional forces, were also investigated. Knee abduction/adduction moments and hip abduction/adduction moments were analyzed as they are consistently related to lower extremity injuries [2].
Additionally, GRF data were divided by the body weight of each participant to normalize as a percent body weight to directly compare values between subjects. Moments were also normalized to participant’s weight in kg offered by Visual3D software.

A repeated measures ANOVA and Tukey HSD post-hoc test methods were used to analyze the data using SPSS 18.0 for Windows (IBM Corporation, Armonk, NY). The significance level was set at 0.05.

Results
Effect of gait by surface and slope
Several statistically significant differences were found between hard and sand surfaces: maximum vertical impact force, maximum vertical thrust force, mean M/L (medial/lateral) GRF, maximum braking force, maximum propulsive force and mean knee A/A (abduction/adduction) moment. It was found that the effect of slope was statistically significant for maximum vertical impact force, maximum vertical thrust force, mean M/L GRF, maximum braking force and mean hip A/A moment. The maximum vertical thrust force, mean M/L GRF, maximum propulsive force and mean hip A/A moment and were found to be statistically significant by surface and slope interaction. Forces and moments for continuous curves by surface and slope interaction effects are described in Figure 4 and Figure 5.

Effect of gait between MOLLE and ALICE
Knee and hip moments were statistically significant when a load was carried. Maximum vertical impact force, maximum vertical thrust force, mean M/L GRF, maximum braking force, maximum propulsive force and mean hip A/A moment had statistically significant interaction effects by backpack and surface. Maximum vertical impact force, maximum braking force, maximum propulsive force and mean hip A/A moment showed statistically significant interaction effects by backpack and slope. The forces and moments for continuous curves by backpack and surface interaction effects are shown in Figure 6 and Figure 7.

Discussion
The objective of this study is to understand the kinetic effect of gait when walking on a sand surface and to investigate the differences between MOLLE and ALICE backpacks on various surface conditions.

The maximum vertical impact force was greater on sand surface than on hard surface; however, maximum thrust force was greater on hard surface than on sand surface. Maximum vertical thrust forces decreased on uphill and increased on flat and downhill for both sand and hard surfaces. The maximum vertical impact force increased as load was added, but there was no significant difference detected between backpacks.

From the current results, sand surfaces may pose greater lower extremity injury risk, based on the maximum vertical impact force, although specific injury mechanisms were not clearly explained by the current study. Hard surface had greater maximum thrust forces, which indicates more effective and efficient gait than sand surfaces. However these forces may increase the chance of foot strain injury due to the greater vertical thrust force concentrating on the foot metatarsal bone.
It was reported that metatarsalgia injury was one of the main recorded acute injuries among 218 infantry soldiers during a 5-day road marching study (8 cases out of a total 68 injuries) [2].

The mean M/L GRF was greater on a sand surface compared to a hard surface. A significant mean M/L GRF increase was observed on the sand downhill condition. On a slant surface it is critically important to balance the body from excessive M/L sway. Previous research confirmed that increased M/L sway were observed to avoid fall injuries [28]. In addition to the slanted surface, mean M/L GRF increases with the addition of a load [7]. From a backpack/surface interaction effect, the sand surface showed a statistically significant increase for mean M/L GRF than the hard surface with added load. However, no difference was found between MOLLE and ALICE backpacks.

Both the maximum braking and the maximum propulsive forces increased significantly on a hard surface, compared to a sand surface. Downhill had greater braking force than flat or uphill for both hard and sand surfaces. The maximum propulsive force was not observed to be a statistically significant interaction effect, but sand downhill showed increased values. There were significantly increased maximum braking and maximum propulsive forces observed for both MOLLE and ALICE backpacks. Kinoshita (1985) found that the possible reason for foot blisters during military marching was the higher pressure on the foot causing greater anterior/posterior movement through increased braking and propulsive forces [32]. Foot blisters were investigated for 16 cases out of 24 injuries in a 20-km road march study and 43 cases out of 68 injuries in a 5-day, 161-km road marching study [2]. Blisters are the most common injury type in road marching studies. There was a significant increase in maximum braking force for ALICE over MOLLE among load conditions. The maximum braking force and the maximum propulsive force for ALICE were greater than those for MOLLE in regards to backpack/surface interaction effect and backpack/slope interaction effect.

During gait, extended hip abduction/adduction (A/A) moment is associated with high risk of injury [28,29]. The current research found that increased hip A/A moment was observed with the backpack condition. On the sand surface, the maximum hip A/A moment was greater than the value on the hard surface and the minimum hip A/A moment was smaller than that observed on the hard surface. Hip A/A moment was twice as large on the sand surface with a backpack in comparison to that observed on the hard surface without a backpack (Figure 4). This indicates that greater risk injury was assumed while walking on the sand surface with a backpack.

Knee joint injury and degeneration are risks that are likely related to an increased knee abduction moment during walking with a heavy backpack [30]. Hurwitz, et al (1998) indicated that there was a statistically significant relationship between knee adduction moments and knee osteoarthritis [31]. This study showed that a greater mean knee A/A moment occurs when on a sand surface than on a hard surface, and
when wearing backpacks than without such external loading (Figure 4).

It has been observed that load is the major contributing factor for multiple injuries [3,4,13]. Current research has confirmed this fact by reporting that mean hip A/A moment and mean knee A/A moment increased 48% and 53% respectively with backpacks as compared to no-backpack conditions (Figure 8).

![Figure 8. Moments by Load Types.](image)

**Conclusion**

Overall, walking on a sand surface or wearing a heavy military backpack appear to result in greater injury risk due to increased vertical impact force and decreased vertical thrust force, which has been shown to increase lower limb overuse injury and reduce comfort. Higher injury risk is expected with an added load. This was determined by the increase in measured knee abduction/adduction and hip abduction/adduction moments. Both of which are closely related to hip injury and knee osteoarthritis.

As evidenced by the results, wearing a military backpack results in an increase in ground reaction forces, knee moments and hip moments. Prolonged exposure to these increased forces and moments likely contributes to common injuries including stress fractures, knee pain, foot blisters and metatarsalgia. Sand surfaces may increase overuse injuries due to higher impact forces. The ALICE (0.472 Nm/kg) backpack has slightly greater lower limb injury potential compared to MOLLE (0.462 Nm/kg). This seemingly insignificant amount of moment would result in a significant amount of additional joint loading during a prolonged amount of time.

It is obvious that reducing the total load seems to be the most simple and quick solution. This could be accomplished by using lighter weight equipment and by packing only necessary items based on operations.

Future work should study the advantage of using a different packing strategy that focuses on including different items depending on each operation, instead of applying a general packing strategy to all military operations. Equipment designed with different materials that are lighter weight will also decrease the potential for lower limb injuries and increase operation performance. Finally, when training on different terrain, changes in lower extremity loading should be used as guidelines to reduce exposure to factors that may lead to overuse injuries, falls, and blisters.

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