THE EFFECT OF CARRYING A MILITARY BACKPACK ON A TRANSVERSE SLOPE AND SAND SURFACE ON LOWER LIMB DURING GAIT

by

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STATEMENT OF DISSERTATION APPROVAL

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ABSTRACT

Marching while carrying a backpack load is the most common activity in the army so being able to endure such a task is required of all military personnel. It is a predictable source of common injuries. Lower limb injuries in particular are caused not only by the extra load but also by the type of surface on which the soldier marches. The objective of this study was thus to expand on the current knowledge of the biomechanical effects of loads by investigating lower limb gait parameters on a sand surface while carrying a military backpack.

Twenty healthy male participants were recruited from among students at the University of Utah who fit the current U. S. military recruitment criteria. The independent variables controlled were the surface type (i.e. hard and sand), slope (i.e. flat and slant), backpack type (i.e. no load, MOLLE, and ALICE), and marching speed (i.e. self-selected and 4 km/h). Data acquisition was performed using 16 NaturalPoint cameras, AMASS software, and 4 force plates.

Over all, it was observed that a decrease in cadence, a decrease in stride length, and an increase in double support time occurred as load was added. In terms of the effects of slope, an increase in double support time and a decrease in stride width were found to occur on the slanted surface as compared to the flat surface. As for the effects of surface type, a decrease in cadence, double support time, and stride length was observed on the sand surface as compared to the hard surface. There was also found to be a general increase in ankle dorsiflexion/plantarflexion, knee flexion/extension, and hip abduction/adduction RoM (Range of Motion) angle on the sand surface as compared to the hard surface. On the whole, walking on a sand surface thus increased M/L GRF, increased vertical impact force, decreased vertical thrust force, and increased knee abduction/adduction moment.

No difference was detected between the MOLLE and ALICE backpacks in terms of resulting cadence, double support time, and stride length. However, a statistically significant increase in stride width was observed with the MOLLE as compared to the ALICE pack. The MOLLE also influenced a statistically significant increase in hip abduction/adduction RoM angle as compared to the ALICE. The ALICE backpack in turn resulted in increased hip A/A moment and higher braking/propulsive forces. Although all of these differences were statistically significant, they are not substantial enough to be considered practically meaningful.

From the findings of this research, it is recommended that military training and general operations be minimized in sand environments in order to reduce the injury potentials discussed above. In unforeseen or unavoidable cases where exposure to such terrain is prolonged, reducing overall load thus needs to be considered to reduce injury potential.

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CHAPTER 1

INTRODUCTION

Literature Review

In 1996, the Armed Forces Epidemiological Board (AFEB) Injury Prevention and Control Work Group reported that injuries were the most significant threat to the U.S. military personnel, with musculoskeletal injuries being the leading cause of hospitalizations of military personnel [1]. In 2006, there were 743,547 musculoskeletal injuries among nondeployed military service members (Air Force, Army, Marines, and Navy). Of those, lower extremity injuries accounted for 39% and upper extremity injuries comprised 14% of the total injuries. The knee/lower leg and ankle/foot injuries represented 57% and 33% of lower extremity injuries, respectively [2]. There were 108,119 soldiers discharged from the U.S. Army between 1981 and 2005 as a consequence of permanent disabilities. 72% of these cases resulted from musculoskeletal injuries and diseases [3].

Military training activities are required for new recruits and are a source of potential injuries. During the military physical training program, musculoskeletal injury rates were calculated to range from 10-15 per 100 recruits per month for male recruits and 15-25 per 100 recruits per month for female recruits. The majority of these injuries are lower extremity musculoskeletal injuries. It is estimated that there were 53,000 lost training days and $16.5 million in medical costs per year among 22,000 male recruits during 12 weeks of training [4]. Other studies confirm that lower-extremity injuries during military training are very common [1, 5-7].

Carrying a load is a requirement for military personnel and is a predictable source of common injuries. Historically, the load carried by infantry units has been increased [8]. The main effect of load carriage in the lower limbs is the increase in ground reaction forces (GRF), which positively links to overuse injuries [9]. Most importantly, as the load increases, joint loading also increases, producing greater injury potential on the joint [10]. In a 20 km march of infantry soldiers (N = 334) each carrying a total load of 46 kg, 24% of the soldiers suffered one or more injuries. All injuries involved the lower extremities and/or the back [11]. In a 161 km cross country march over 5 days (N=218), 36% of soldiers were injured during the march and 96% of the injuries involved the lower extremities [12].

Along with the load, surface condition is one of the significant factors affecting injuries. One researcher suggested that it is beneficial to include other relevant determinants, which are climate, terrain, and gradient, to determine the soldier's load carriage capability [13]. Another researcher presented an interesting view of surfaces and indicated that a sand surface, which is an unstable surface condition, and a sloped surface, such as a beach or shoulder of a road, increases stresses on the tendons and ligaments of the lower extremity [14].

Purpose of Research and Goals

The purpose of this study is to understand the changes of spatial-temporal, kinematics and kinetics parameters of gait during walking on a sand surface carrying a backpack. The current study will extend the scope of understanding by including transverse slope conditions. Two Army backpacks are examined. They are MOLLE and ALICE backpack types. They are compared to each other and also compared with a no load condition.

Increasing numbers of military personnel are performing operations on uneven surface conditions. This provides greater motivation to conduct research on uneven surfaces. The sand surface used in this study is designed to simulate desert operations in middle-eastern countries. Desert operations demand a heavier load requirement than any other military operations [8]. The energy expenditure of walking on a sand surface requires 2.1 – 2.7 times more than walking on a hard surface; however, little or no information is available on how forces, moments, and other gait parameters are affected by a sand surface [13]. To the author's awareness, this is the only study that has examined complete lower limb biomechanics on sand carrying a backpack. The results of this study will help investigators understand the effects on soldiers, particularly those who must carry a significant load during desert operations. It may also help clarify the risks of backpack carriage during hiking and other civilian recreational activities that might occur in similar environments.

Outline

This dissertation consists of six chapters, including the introduction section, Chapter 1, followed by the general method section, which is Chapter 2. Chapters 3-5 include lower limb effects by surface type, slope, marching speed, and backpack types. Individual chapter titles are:

- Chapter 3 – Effects of carrying a military backpack on a transverse slope and sand surface on lower limb spatial temporal parameters
- Chapter 4 – Effects of carrying a military backpack on a transverse slope and sand surface on lower limb kinematic parameters
- Chapter 5 – Effects of carrying a military backpack on a transverse slope and sand surface on lower limb kinetic parameters

Chapter 6 summarizes the current research and also suggests the future study to gain further understanding of this research topic.

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CHAPTER 2

METHODS

Participants

Twenty healthy male participants volunteered for this study. Participants were carefully selected from a healthy young population who were not currently experiencing any injury or pain in the back or lower extremities or were fully recovered from any prior discomfort, injuries, or disorders that may have affected normal gait. The anthropometric selection criteria were set at the following: age of 18 - 30, height of 161 - 195 cm, and weight of 55 - 87 kg. These were designated to replicate the current military soldiers' recruiting standard [1]. The participants' anthropometric data were measured and recorded, with a mean (±SD) age of 25.1±3.6 years, height of 175.6±64.6 cm, body mass of 74.9±7.7 kg. All participants reviewed and signed an informed consent document approved by the University of Utah Institutional Review Board. They also were notified that they could withdraw from the study at any time during their trials if they felt uncomfortable.

Backpacks and Boots

Two dominant types of military backpacks in current use from the U.S. military were selected; these were the ALICE type backpack and the MOLLE type backpack. The

ALICE (All-purpose Lightweight Individual Carrying Equipment) is a military issue backpack consisting of a sack, aluminum frame, and various straps and supports. The MOLLE (Modular Lightweight Load-carrying Equipment) is used to define the current generation of load-bearing equipment and it is modularized with compatible pouches and accessories. It is a standard for modular tactical gear, replacing the ALICE system used as an earlier load carriage system. The objective of this study was to analyze these designs by measuring spatial-temporal, kinematic, and kinetic parameters for users walking on two surface types (hard vs. sand) and for level and laterally slanted slope surfaces (10 degrees).

The standard backpack load carriage system established by U.S. forces varies by operations; however, the general marching load range is from 25.9kg to 32.7kg [2]. In this study, each backpack has the same load of 29kg (64lbs). This load includes initial backpack weight, all associated accessories, and other devices for data collection. The internal load of each backpack is evenly distributed inside the backpack. The dimension of the MOLLE backpack is 24×32×62 (cm^3) and the ALICE backpack is 23×31×48 (cm^3) (Figure 2-1).

Figure 2-1. MOLLE (left) and ALICE (right) Backpacks

Only one style of U.S. Military boots was worn to minimize any bias error resulting from using different footwear types. U.S. Army issued desert tan BELLEVILLE 790G Gore-Tex combat boots were provided under the cooperation of the University of Utah Military Science department (Figure 2-2)

Tracks and Force Platforms

The current study used customized tracks in order to replicate sand and hard surfaces along with changes in transverse slope conditions. The dimension of the track used is 0.76 m × 7.3 m. Five height adjustable hand cranks were installed on each side of the track to provide transverse slopes. The transverse slope angle that the current study required was 10° (Figure 2-3).

One track was filled with sand to simulate a desert environment. A specific sand type was carefully selected under the guidance of a professor from the Geology department and a former resident of Iraq to best simulate the desert environment in the Middle Eastern region. The other track was covered with ¾ inch reinforced plywood to replicate a hard surface condition.

A total of 4 force plates, 2 (OR6-5-1000 & OR6-7, AMTI, Watertown, MA) for the sand surface and 2 (FP4060-08-1000, BERTEC, Columbus, OH) for the hard surface,

Figure 2-2. Military Boots

Figure 2-3. Two Tracks: Sand and Hard

were used to collect ground reaction data at a sampling rate of 2000 Hz. On the hard surface, participants contacted the force plates directly. The two force plates were isolated from each other and secured to reduce vibration before and after foot contacts. On the sand surface, these force plates were embedded under the sand and isolated by a customized isolation fixture that was originally designed by another researcher [3] (Figure 2-4). This customized isolation fixture was used to reduce the dissipation of force from surrounding sand. Merryweather (2008) confirmed that this force plate isolation technique could serve well to test railroad ballast as well as other surfaces [3].

Figure 2-4. Forceplate Isolation Fixture

Motion Capture System and Markers

Three-dimensional motion data were captured with 16 NatrualPoint V100:R2 cameras and AMASS software at a sampling rate of 100Hz. A custom data acquisition interface was designed with LabVIEW (National Instruments, Version 10.0.1) for force data at a sampling rate of 2000Hz. The captured data were further processed using Visual3D software (modelling) and Vicon Nexus software (trajectory postprocessing).

For static trials, reflective markers were attached bilaterally to the participants at the following locations: anterior superior iliac spine, posterior superior iliac spine, lateral femoral condyle, medial femoral condyle, lateral malleolus, medial malleolus, calcaneus, between the second and third proximal metatarsal heads, and head of the 5th Metatarsus. In addition to the predefined marker set from C-motion, marker clusters were also used on thighs and shanks for static and dynamic tracking purposes (Figure 2-5). A static trial was captured for 6 seconds for each participant in order to calibrate the marker set and to create a model.

Figure 2-5. Dynamic Marker Set

For dynamic walking trials, because the backpacks continually block the PSIS markers, virtual PSIS markers were introduced and measured using thigh clusters. In this regard, two methods of locating PSIS markers were developed and introduced in the following section.

Method 1: Locating PSIS Markers

Accuracy of anatomical landmark identification through marker placement is critical in biomechanical model creation. Regardless of the development of systems, there are situations where current techniques fail to identify landmarks that are hidden or blocked from the environment, or from assistive devices and equipment that interfere with the identification of body segments. This method is developed to demonstrate the effectiveness of an alternate technique to locate anatomical landmarks on the pelvis, back, and shoulders during gait analyses to investigate the effect of being encumbered with a full-frame backpack.

The ability to locate the endpoint of a solid rod with two collinear markers along a straight line is illustrated in Figure 2-6. Multiplying the unit vector by the rod length (l) defines the vector p. This represents the vector from the marker r_3 to the marker r_1 (Equation 2.1). Then the unknown vector r_1 can be calculated using Equation 2.2 where Point ‘o’ describes a point where a marker would be placed when not occluded.

This method can be widely applied to research using 3D motion analysis system, especially, under certain circumstances when external objects block significant anatomical landmarks.

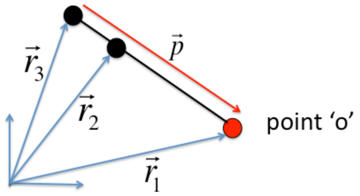

Figure 2-6. Vector Notation to Calculate the Vector *p*

$$\vec{P} = \left(\frac{\vec{r_2}-\vec{r_3}}{|\vec{r_2}-\vec{r_3}|}\right) \times l \qquad (2\text{-}1)$$

$$\vec{r_1} = \vec{r_3} + \vec{p} \qquad (2\text{-}2)$$

Method 2: Locating PSIS Markers

The basic technique is introduced by the Visual3D motion capture system, but the current research team modified and applied this technique to the specific missing markers, which are 2 PSISs. Before collecting dynamic trials or at the very beginning of data collection, it is very important to capture a static trial that has all the markers in place. The static trial has to have PSIS markers in place so that we can use the PSIS marker locations later as a reference point. The first step of this method is to find the hip joint center locations using the relationship between the pelvis and thigh clusters.

Visual3D calculates the hip joint center marker (pink sphere) once the system has noticed 2 ASIS and 2 PSIS markers (Figure 2-7). As femoral head center and hip joint center are identical, the relationship between femoral head center (hip joint center) location and a thigh cluster can be built (Figure 2-7).

The second step is to find the relationship between the PSIS marker location and the other 3 markers, which are virtual femoral head center location (or virtual hip joint center location from thigh clusters) and 2 ASIS markers (Figure 2-8). In the static

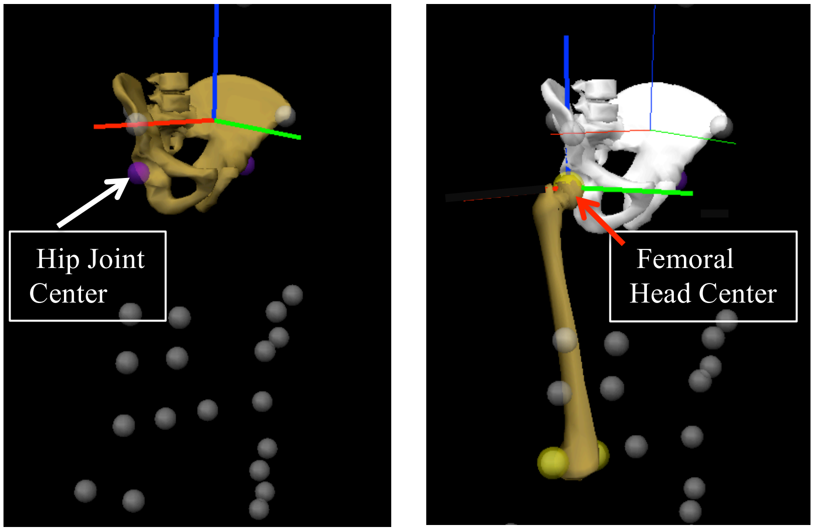

Figure 2-7. Hip Joint Center (left) and Femoral Head Center (right)

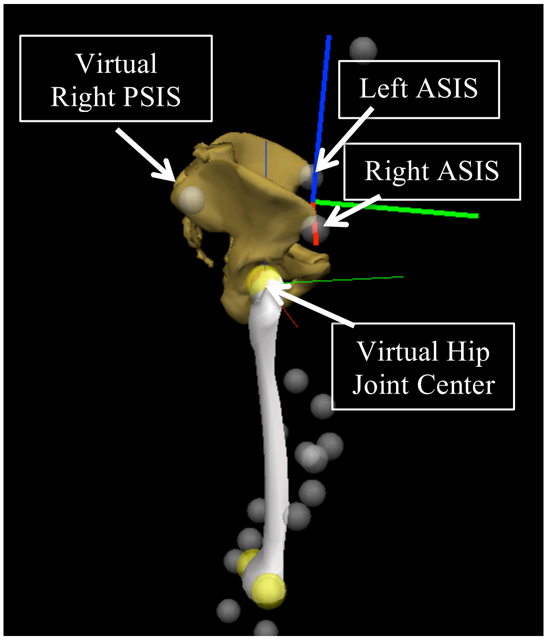

Figure 2-8. Virtual PSIS Marker

capture, we have the location information of PSIS markers, so we could make this relationship easily. Now we have a virtual PSIS marker location. This location is always identifiable by the other 3 markers even if that marker is missing or blocked.

Protocol

The independent variables being controlled for in this study are: surface type (hard, sand), slope (flat, slant), backpack type (no load, MOLLE, ALICE), and marching speed (self-selected and 4 km/h). Each backpack weighed 29kg (64lbs) and the load was evenly distributed inside the backpack. The marching speed of 4km/h was selected based on the U.S. Army Field Manual 21-18 [4]. Participants were guided to walk in two different walking speeds. Self-selected speed was chosen by the participant as their normal walking speed. For 4km/h, they were guided to follow the flag that was moving constantly at 4km/h. Three good trials were chosen for each condition and the total 72 trials were acquired for each participant.

surface (2) × slope (2) × backpack (3) × speed (2) × trial (3) = 72 total trials

A randomized block design was used, where the track (surface and slope) was the blocking parameter, meaning all necessary trials were performed for that specific blocked condition.

It took 4 - 5 hours to finish data collection for each participant, including preparation time. Participants were asked to walk down a 24 ft. walkway approximately 144 times. The total walking distance was projected to be approximately 0.67 miles and the total estimated time walking during the study was approximately 40 minutes. Right foot was always in downslope and left foot always in upslope. Two force plates measured the forces of each foot individually.

Markers were placed according to Visual3D guidelines provided by C-Motion. These markers described the location of each body segment at any point in time for calculating joint positions, velocities, and accelerations. After the participant was equipped with the markers and every calibration initial preparation process was done, the participant was asked to walk down the track. After collecting 3 trials per condition, each participant was provided with enough recovery time to reduce the fatigue effect. Additional force plate calibration measurements were taken each time the slope configuration was changed.

Data Analysis

The performance of the proposed model was evaluated using traditional statistical and epidemiological techniques. Temporal, kinematic, and kinetic parameters were recorded and analyzed. Key variables of gait analysis were temporal parameters, joint angles, joint moments, and ground reaction forces.

Double support time, cadence, stride length, and stride width were calculated and averaged by each condition. Stride length and stride width were normalized by the height of the participant. Two walking speeds: self-selected speed and 4km/h. Cadence was measured in walking rate of steps in km per hour and normalized to participant's height.

Ankle, knee, and hip range of motion angle data were calculated from HS (heel strike) to HS and normalized by 101 data points as 0% at HS and 100% at HS. Hip and knee flexion/extension angle at HS and ankle flexion/extension angle at TO (toe off) were measured.

GRF data were sampled at 2000Hz. Each gait cycle generally had two peaks that happened after HS and before TO. Maximum braking/propulsive forces, ankle moment, knee moment, and hip moment were also measured and normalized by 101 data points as well. Ground reaction force data were divided by the body weight of each participant to normalize and acquire the percent body weight for easy comparison of data.

Video data and analog data were filtered with a cut-off frequency of 6 Hz using the function in Visual3D prior to further data analysis. Additionally, ground reaction forces and moments were divided by the body weight of the participant to achieve percent body weight. Moments were also normalized using a normalizing function in Visual3D.

Statistical Analysis

Data were compared for the following variables: surface type (sand vs. hard), slope (0 vs. 10°), walking speed (self-selected vs. 4km/h), and backpack type (no load vs. MOLLE vs. ALICE) using the analysis of variance (ANOVA). The significance level was set at 0.05. Post-hoc tests were conducted using Tukey LSD to run the pairwise comparison. The statistical tests were performed using SPSS 18.0 for Windows (IBM Corporation, Armonk, NY).

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CHAPTER 3

THE EFFECT OF CARRYING A MILITARY BACKPACK ON A TRANSVERSE SLOPE AND SAND SURFACE ON LOWER LIMB SPATIAL-TEMPORAL PARAMETERS DURING GAIT

Abstract

Understanding the spatial-temporal effects of a military load carriage on a sand surface is important to those performing military operations in the desert, for this may aid in reducing the risk of lower limb overuse injuries. Twenty healthy male participants who met the military's recruiting criteria participated in this study. Two surface types, hard and sand, and two different types of backpacks, ALICE and MOLLE, were evaluated. The results of the current study confirmed previous findings that a significant decrease in cadence and stride length occurs with carried loads. A significant increase in double support time occurred as with the load, in addition to an increase in double support time on the slant surface. Stride width significantly decreased on the slant surface compared to the flat surface. Interestingly, cadence, double support time, and stride length decreased on the sand surface, as compared to the hard surface. The trials using the MOLLE backpack had greater stride width than the ALICE backpack on a slanted surface, which may indicate that the MOLLE requires a greater base of support to stabilize the body.

Introduction

Studies pertaining to spatial-temporal gait parameter changes commonly agree that there is an increase in double support time [1-4], a decrease in stride length [1, 3, 5], and an increase in stride frequency [2, 6] as the load is increased. Researchers found that greater double support time decreased trips and falls by providing greater control and stability during walking [1, 2]. It is also suggested that increasing stride frequency and decreasing stride time could help reduce stress on bones and may help prevent stress fractures [2]. Another study found that spatial-temporal gait parameters, such as walking speed, stride length, and cadence did not show a difference between no load, 15% BW load, and 30% BW load conditions [7].

Walking on uneven or irregular surfaces resulted in an increased knee flexion angle during ground contact [8]. Previous researchers found that sandy surface increased mechanical energy costs and the rocky surface condition changed the spatial-temporal parameters that might increase lower extremity injuries [9-11].

Injuries in the military are recognized as the leading health problem for soldiers; studies show that lower extremity injuries are more dominant than upper extremity injuries [6, 12-14]. Much of the current research focuses on the effects on the lower extremity movements as the load increases [7, 15], irregular surfaces are encountered [16], and transverse slope are traversed [17]. Studies also address the load-speed interaction effects [18].

This study aims to understand the effects of carrying a military backpack on simulated desert terrain (fine sand) and a slanted surface (10 degrees: left to right) on spatial-temporal parameters during gait. The current study also focuses on evaluating the effects of two military backpacks on human gait. The research hypothesized that two backpacks, MOLLE and ALICE, would have different effects on spatial-temporal parameters, and that these effects are modified by surface conditions.

Method

Participants

Twenty healthy male participants volunteered for this study. Participants were carefully selected from a healthy young population who were not currently experiencing an injury or pain in the back or lower extremities or were fully recovered from any discomfort, injuries, or disorders that may affect normal gait. The anthropometric selection criteria were set at the following: age of 18 - 30, height of 161 - 195 cm, and weight of 55 - 87 kg. These were designated to replicate the current military soldiers' recruiting standard [19]. The participants' anthropometric data were measured and recorded, with a mean (±SD) age of 25.1±3.6 years, height of 175.6±64.6 cm, and body mass of 74.9±7.7 kg. All participants reviewed and signed an informed consent document approved by University of Utah Institutional Review Board.

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Protocol

The independent variables being controlled for in this study are: surface type (hard, sand), slope (flat, slant), backpack type (no load, MOLLE, ALICE), and marching speed (self-selected, 4 km/h). Each backpack weighed 29kg (64lbs) and the load was evenly distributed inside the backpack.

Participants were guided to walk in two different walking speeds. The marching speed of 4km/h was selected as the normal marching speed for foot troops based on the U.S. Army Field Manual 21-18 [21]. They were guided to follow the flag that was moving constantly at 4km/h at the participant's eye height. Self-selected speed was freely chosen by the participant as their normal walking speed. To minimize the learning effect by the forced marching speed, a randomized block design was used where the track (surface and slope) was the blocking parameter. Three good trials were chosen for each condition and the total 72 trials were acquired for each participant.

Markers were placed according to Visual3D guidelines provided by C-Motion. These markers described the location of each body segment at any point in time for calculating joint positions, velocities, and accelerations. After the participant was equipped with the markers and every calibration initial preparation process was done, the participant was asked to walk down the track. After collecting 3 trials per condition, each participant was provided with enough recovery time to reduce the fatigue effect. Additional force plate calibration measurements were taken each time the slope configuration was changed.

Data Analysis

The performance of the proposed model was evaluated using traditional statistical and epidemiological techniques. Key variables of gait analysis in spatial-temporal parameters, such as double support time, cadence, stride length, and stride width, were calculated and analyzed. Stride length and stride width were normalized by the height of the participant. Two walking speeds: self-selected speed and 4km/h are selected. Cadence was measured in walking rate of steps in km per hour and normalized to participant's height. GRF data were sampled at 2000Hz and used to measure events for gait cycle recognition. Percent cycle data were calculated from HS (heel strike) to HS and normalized by 101 data points as 0% at HS and 100% at the following HS. Video data and analog data were filtered with a cut-off frequency of 6 Hz using the function in Visual3D prior to further data analysis. Error bars in each bar graph represent standard deviation of the data.

Statistical Analysis

The repeated measures analysis of variance (RM ANOVA) method was used. All main effects were analyzed by comparing the following independent variables: surface type, slope, walking speed, and backpack type. All two-way interaction effects were also analyzed. The significance level (α) was set at 0.05. Post-hoc tests were conducted using Tukey LSD to run the pairwise comparison for load types. The statistical tests were performed using SPSS 18.0 for Windows (IBM Corporation, Armonk, NY).

Results

Results from spatial-temporal data showed that double support time, cadence, and stride length were significantly different in all main effects. Stride width was statistically significant only by slope condition (Table 3.1). Stride length and stride width were normalized by each participant's height.

Surface Effect

There was a statistically significant difference between hard and sand surfaces for double support time, cadence, and stride length (*p*<0.001, *p*=0.003, and *p*=0.001, respectively). Results are shown in Figure 3-1, Figure 3-2, and Figure 3-3.

Slope Effect

It was found that the effect of slope was significant for double support time, cadence, stride length, and stride width (*p*=0.047, *p*=0.025, *p*=0.011, and *p*<0.001, respectively). Values for these parameters are described in Figure 3-4, Figure 3-5, Figure 3-6, and Figure 3-7.

Walking Speed Effect

There were several statistically significant differences between self selected speed and 4km/h: double support time (*p*<0.001), cadence (*p*<0.001), and stride length (*p*=0.032). These results are shown in Figure 3-8, Figure 3-9, and Figure 3-10.

Table 3-1. Summary of the main spatial-temporal effects

	Surface		Slope		Walking Speed		Backpack		
Condition	Hard	Sand	Flat	Slant	Self	4km/h	No Load	MOLLE	ALICE
Cadence (km/h)	4.29	4.088^{*}	4.22	4.160^{*}	3.99	4.390^{*}	4.281	4.146^{*}	4.140^{*}
Double Support (s)	0.36	0.283^{*}	0.32	0.324^{*}	0.34	0.304^{*}	0.286	0.337^{*}	0.339^{*}
Stride Length (m)	0.78	0.745^{*}	0.77	0.757^{*}	0.76	0.764^{*}	0.77	0.755^{*}	0.757^{*}
Stride Width (m)	0.07	0.071	0.07	0.068^{*}	0.07	0.07	0.071	0.072	0.070^{**}

* indicates statistical significance ($p<0.05$) compared to control conditions (hard, flat, self, no load).

** indicates statistical significance ($p<0.05$) compared to MOLLE.

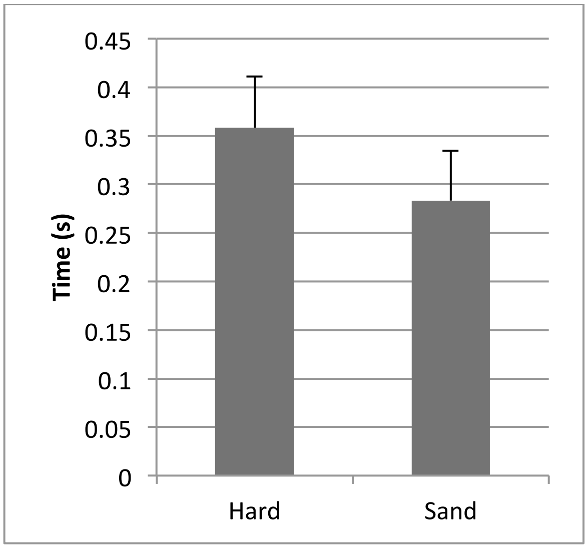

Figure 3-1. Double Support Time by Surface (*p*<0.001))

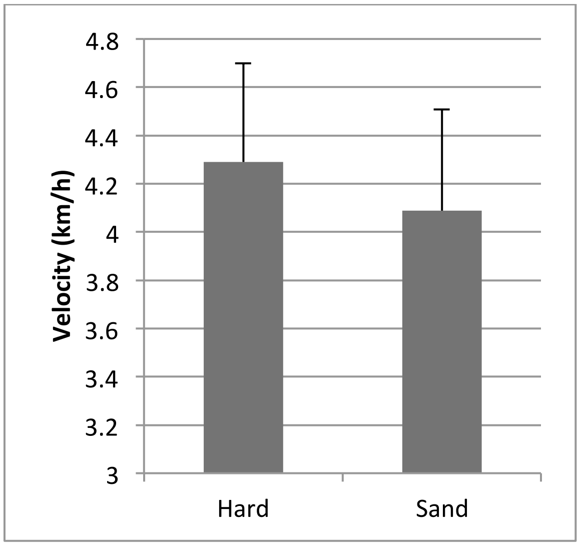

Figure 3-2. Cadence by Surface (*p*=0.003)

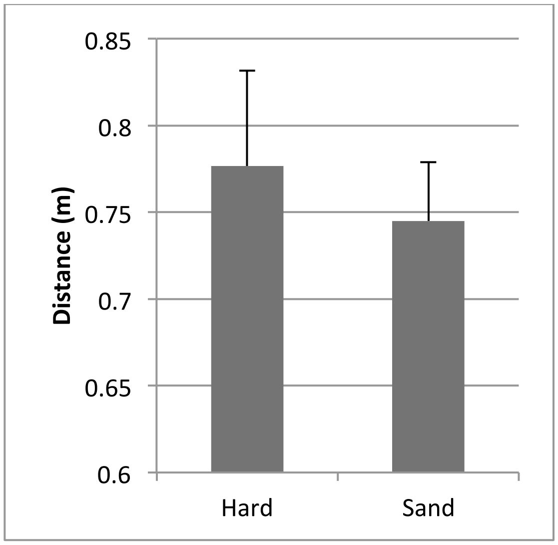

Figure 3-3. Stride Length by Surface (*p*=0.001)

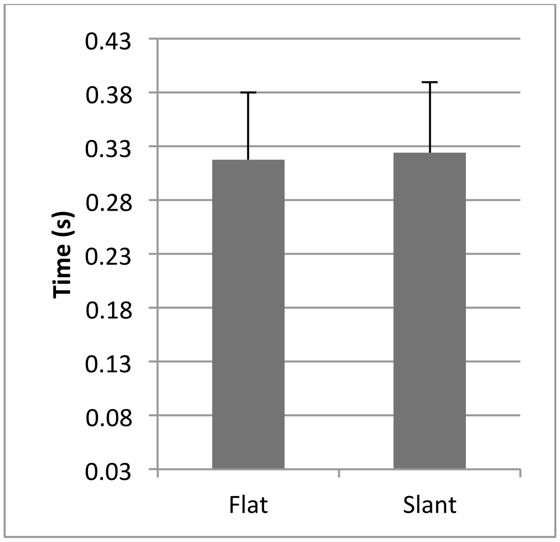

Figure 3-4. Double Support by Slope (*p*=0.047)

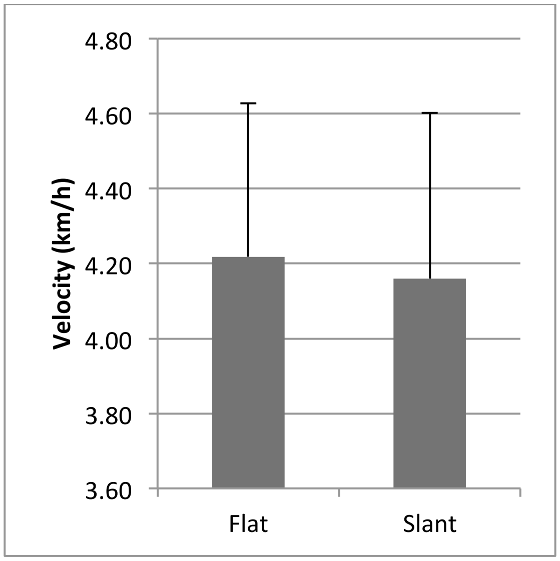

Figure 3-5. Cadence by Slope (*p*=0.025)

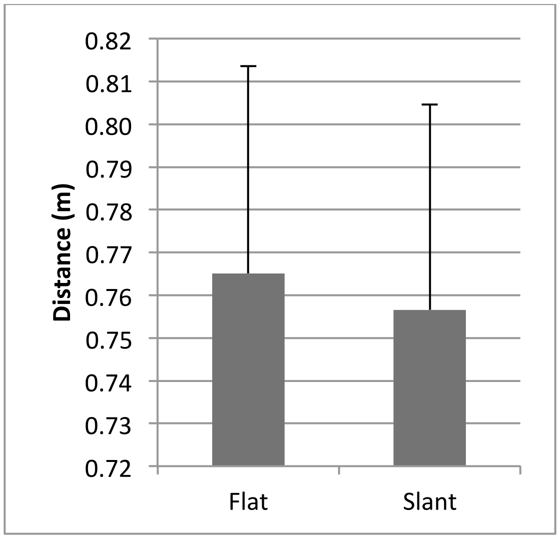

Figure 3-6. Stride Length by Slope (*p*=0.011)

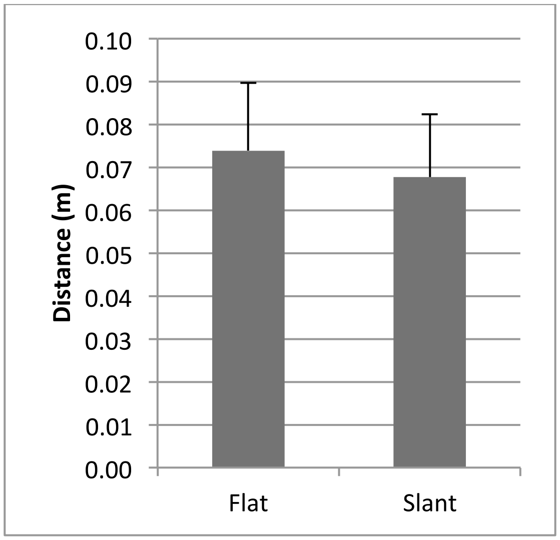

Figure 3-7. Stride Width by Slope (p<0.001)

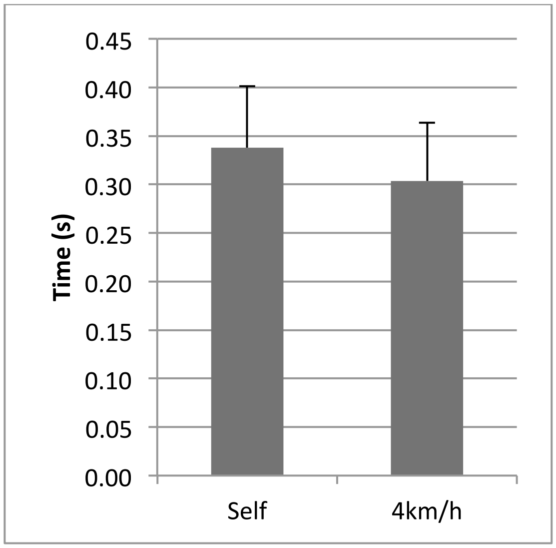

Figure 3-8. Double Support Time by Walking Speed (p<0.001)

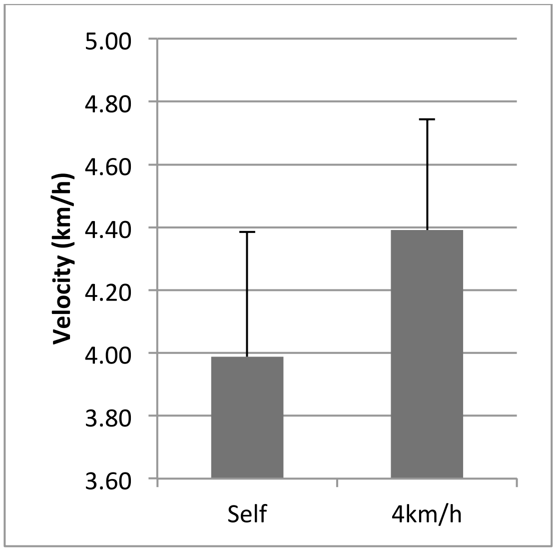

Figure 3-9. Cadence by Walking Speed (*p*<0.001)

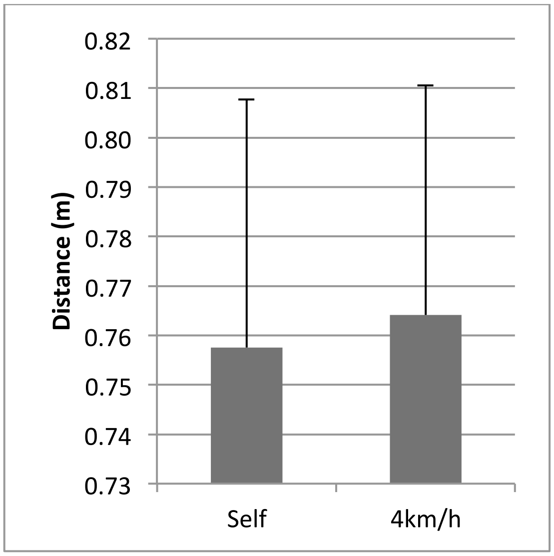

Figure 3-10. Stride Length by Walking Speed (*p*=0.032)

Backpack Effect

A statistically significant difference was found for double support time, cadence, and stride length among load conditions (*p*<0.001, *p*<0.001, and *p*=0.001, respectively); however, no statistical difference was found between MOLLE and ALICE. Detailed values are described in Figure 3-11, Figure 3-12, and Figure 3-13.

Surface × Backpack Interaction Effect

Surface and backpack type had a statistically significant interaction effect (*p*=0.004) on stride length. The description is shown in Figure 3-14.

Discussion

Cadence was significantly lower on the sand surface compared to the hard surface. There was no statistical significance detected in the surface and slope interaction effect; however, a trend in decreasing cadence was observed in the following order of surface/slop combinations: hard flat (HF), hard slant (HS), sand flat (SF) and sand slant (SS) (Figure 3-15 and Figure 3-16). This indicates that irregular surfaces reduced cadence and reduced speed [11]. Several studies confirmed that walking on a sand surface requires more energy than walking on a hard surface [10, 22]. Such an increase in energy expenditure could likely result in a soldier becoming fatigued more easily and could increase their potential for lower extremity injuries [12, 23-25]. As walking on a sand surface results in decreased cadence and increased fatigue, the standard marching speed, 4km/h, should be adjusted (i.e. reduced) while in sandy environments. If a backpack load is applied to a soldier, the marching speed should be reduced even further to reduce lower

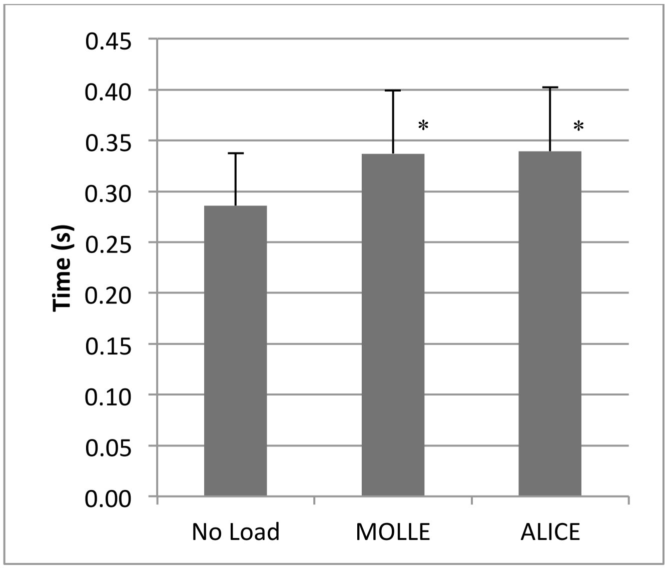

Figure 3-11. Double Support Time by Backpack (*p*<0.001).
* indicates statistical significance (*p*<0.05) compared to No Load.

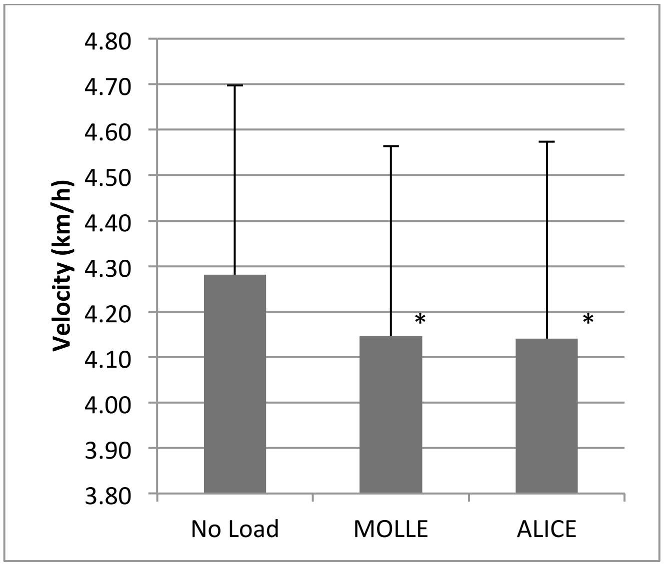

Figure 3-12. Cadence by Backpack (*p*<0.001).
* indicates statistical significance (*p*<0.05) compared to No Load.

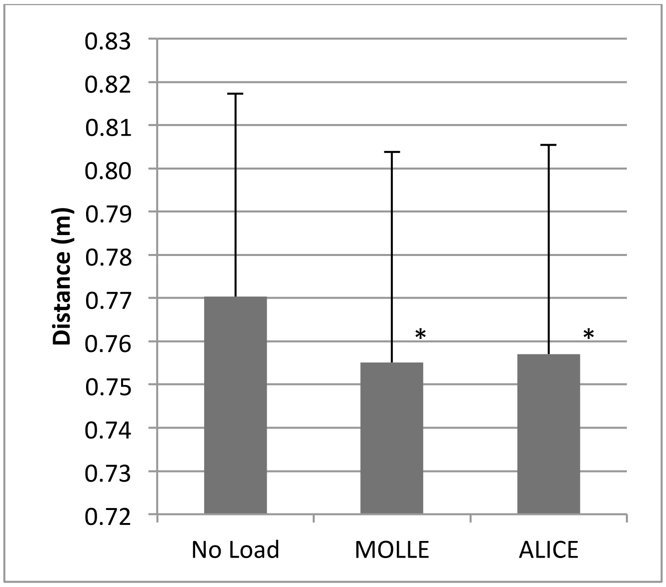

Figure 3-13. Stride Length by Backpack (p=0.001)
* indicates statistical significance (p<0.05) compared to No Load.

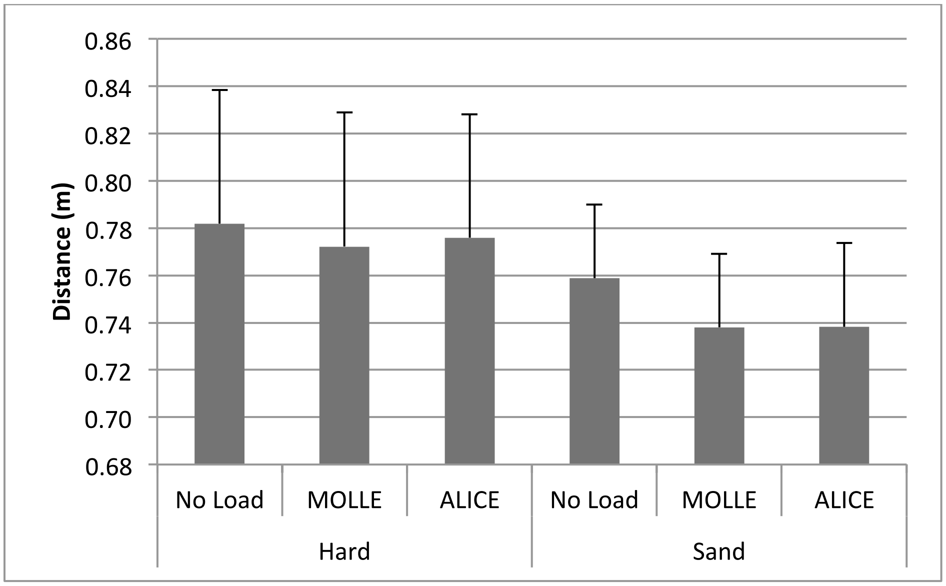

Figure 3-14. Stride Length by Surface and Backpack (p=0.004)

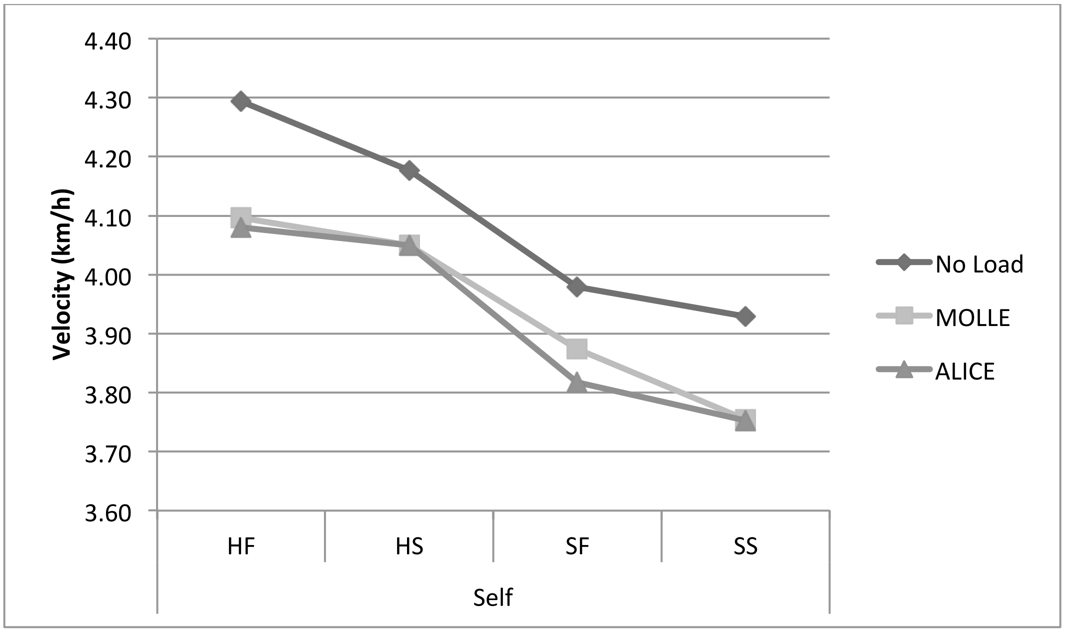

Figure 3-15. Speed Changes over Surface Conditions (Self Speed)

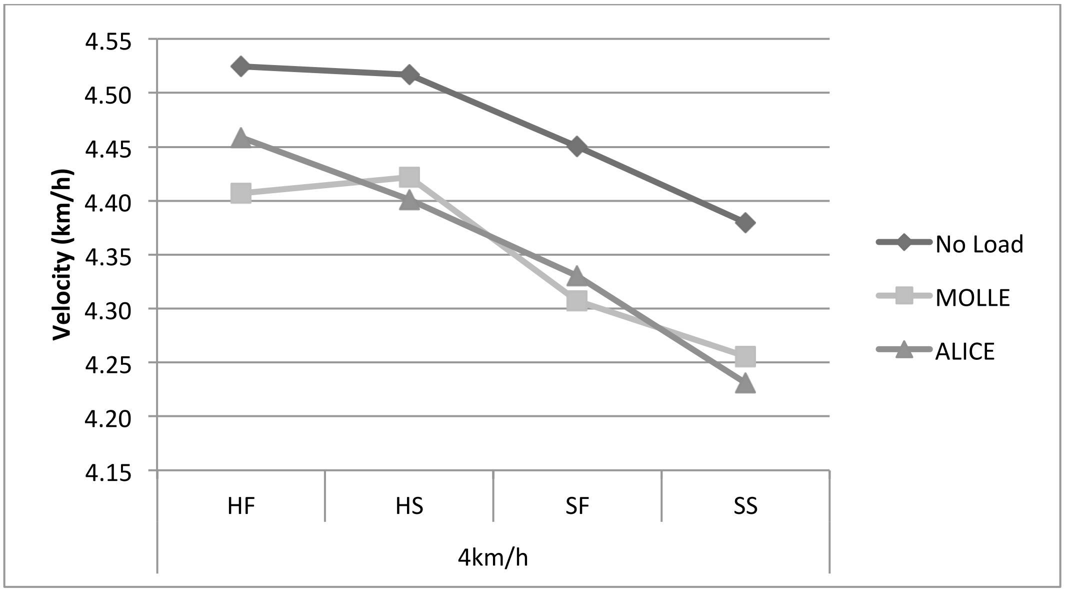

Figure 3-16. Speed Changes over Surface Conditions (4km/h)

extremity musculoskeletal injuries [3, 12, 23-27].

It was found that double support time increased as the load increased, which is similar to other research findings [3, 5, 18, 28]. Such an increase in stability provided by increased double support time would decrease the potential of trips and falls [5, 18]. It was also found that double support time increased as the slope increased and that it was lower on the sand surface compared to the hard surface ($p<0.001$) (Figure 3-17). This makes sense because in general on a hard surface, increased stability can be achieved by increasing double support time, while on a sand surface, greater stability can be achieved by increasing number of steps [29]. It was also observed that double support time decreased as walking speed increased. Overall, double support time was found to have a statistically significant surface and speed interaction effect ($p=0.008$), with the lowest double support time being seen on the sand-slant surface with self-selected speed (Figure 3-18). It is generally believed that increased double support time during load carriage provides greater stability and control [1]. Thus it can be concluded that 1) increased double support time could reduce trips and falls during military load carriage [3] and 2) based on the double support findings in this study, walking on a sandy slanted surface in military operations could be proven to result in a higher risk of lower extremity musculoskeletal injuries due to decreased stability.

Walking with the backpack resulted in a significant decrease in stride length compared to the 'No Load' condition. This result is supported by other studies that have similarly shown that stride length decreases as load is added [1, 5]. Attwells et al. (2006), in particular, confirmed that stride length decreases as load increases and explained that this occurs as a result of trying to achieve greater stability [5]. This relationship

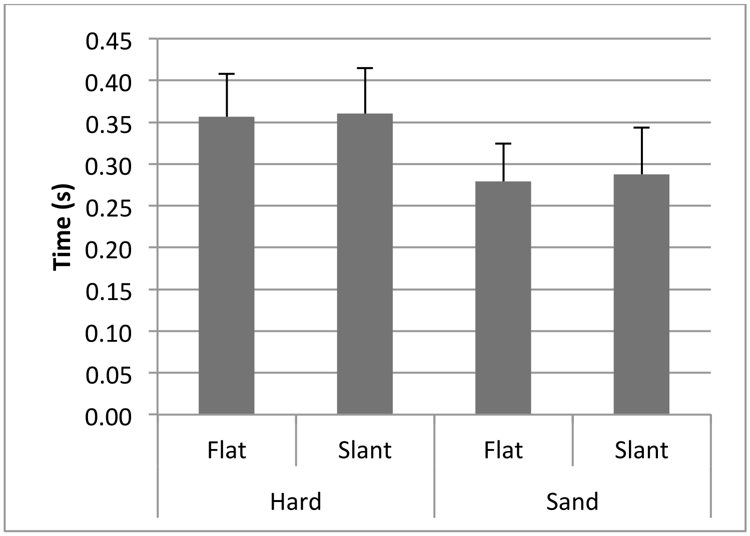

Figure 3-17. Double Support Time by Surface and Slope (*p*<0.001)

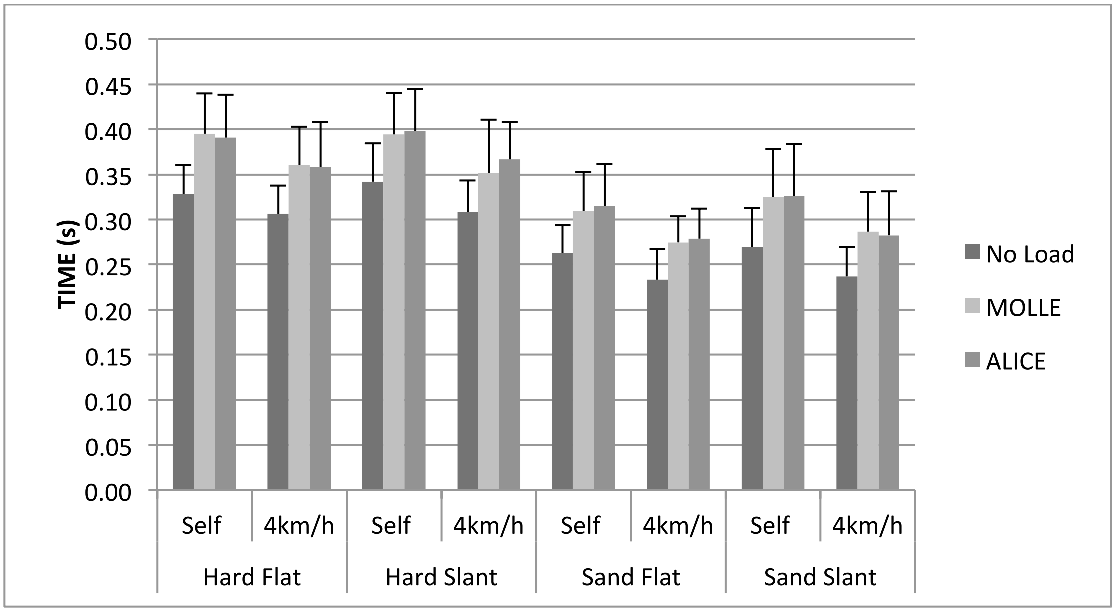

Figure 3-18. Double Support Time by Surface and Speed (*p*=0.008)

between stride length and stability can be used to compare not only load effects, but surfaces as well. For example, in general, sandy surfaces result in less stability than when on a hard surface; therefore, it would be expected that a decreased stride length would occur on the sand, which is what the current study confirms (Figure 3-14).

This could be interpreted as meaning that walking on a sand surface is more dangerous than walking on a hard surface even with the heavy backpack. In order to investigate this assumption, decreased stride length and decreased double support time on both hard and sand surface were investigated with the added load. Interestingly, double support time on the sand surface was shorter than that on the hard surface (which was not supported by the previous study) [5]; however, the sand surface increased stability by increasing step/min by about 3% compared to the hard surface. The sand surface provided less thrust compared to the hard surface and the sand surface was unstable as well, so the shorter stride length was necessary to generate enough force at toe-off and enough torque to propel the body from the surface [30].

This current study showed that stride width was greater on the slanted surface compared to the flat surface; however, no significant difference was found between surface types nor between marching speeds (p=0.928 and p=0.095). Unlike other spatial-temporal parameters [31], stride width did not change significantly as load increased (p=0.097); however, MOLLE had a statistically greater stride width than ALICE (p=0.008) (Figure 3-19). One of the possible reasons for wider stride widths with MOLLE is the greater medial/lateral movement of the MOLLE backpack. (The medial/lateral RoM of MOLLE backpack is 7.1% greater than ALICE backpack.)

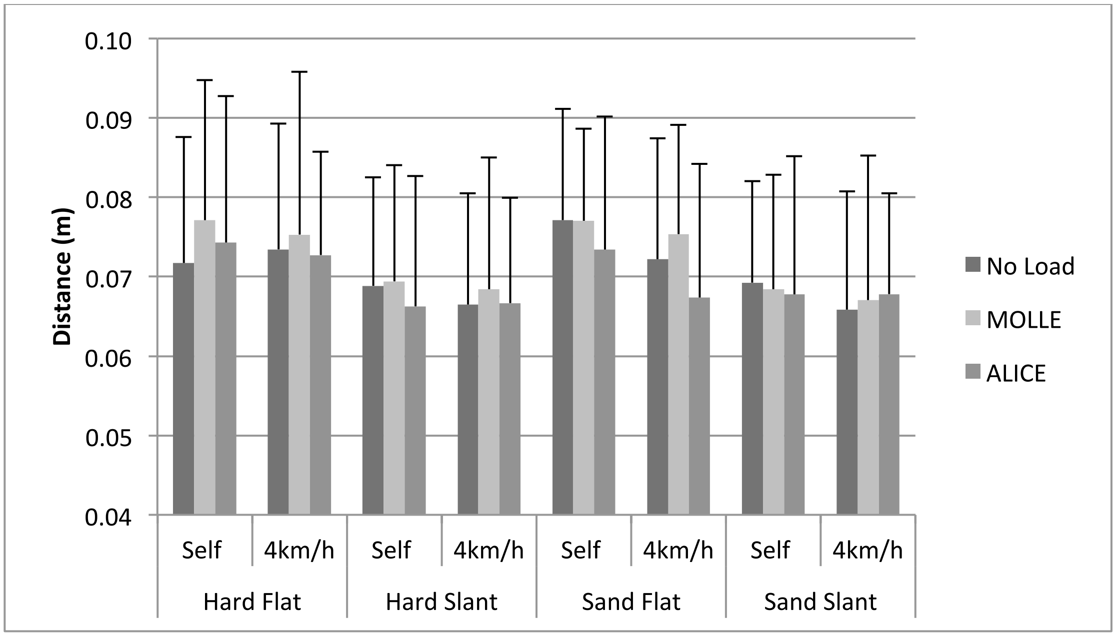

Figure 3-19. Stride Width by Backpack and Speed (*p*=0.008)

Changes in stride widths in general are meant to maintain stability over unstable walking conditions. Though the difference is relatively small between the backpacks (MOLLE is 7.2cm and ALICE is 7.0cm), it may lead to a much greater difference in cumulative effect on military soldiers who are marching for long periods of time for several days.

Conclusion

The main objective of this study was to understand spatial-temporal parameters on different surface conditions and to identify the differences between the parameters among various load conditions. Results showed and supported the conclusions of previous researchers (i.e. that a significant decrease in cadence and stride length occurs and a significant increase in double support time occurs as the load increases). An increase in double support time was found on the slanted surface compared to the flat surface and as the load increased. Stride width significantly decreased on the slanted surface compared to the flat surface. There were some interesting results found on the sand surface as well. Statistically significant decreases in cadence, double support time, and stride length were observed on the sand surface as compared to hard surface. Walking on a sandy surface with a military backpack would thus be expected to increases fatigue, so the standard marching speed should be reduced to reduce lower extremity musculoskeletal injuries. No significant difference was detected between MOLLE and ALICE for cadence, double support time, or stride length. However, a statistically significant increase was observed for MOLLE compared to ALICE in stride width which could result in significantly different effects during road marching operations lasting long periods of time.

For the forced marching trials (4km/h), cadence decreased about 3% for the no load condition and it decreased about 5% for the ALICE backpack. For the self-selected speed, cadence decreased even greater, which is about 8.4% for no load and 8.5% for both MOLLE and 8.1% for the ALICE. It turned out that the stride length decreased on the sand surface and with the backpack as well. Therefore, in conclusion, in case of a forced marching military operation, soldiers should either increase the frequency of steps or increase stride length to catch up with the pace. In addition, marching speeds should be reduced at least 8% on sand slant surfaces as compared to hard flat surfaces in order to reduce potential fatigue and stress on the legs.

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CHAPTER 4

THE EFFECT OF CARRYING A MILITARY BACKPACK ON A TRANSVERSE SLOPE AND SAND SURFACE ON LOWER LIMB KINEMATIC PARAMETERS DURING GAIT

Abstract

The objective of this study was to understand the kinematic effects of walking on a sand surface while carrying two different types of backpacks (MOLLE and ALICE). Twenty healthy male participants were recruited among students from the University of Utah. Two surface types (sand and hard), two slopes (flat and slant), three load conditions (no load, MOLLE, and ALICE) were used in this study. Results showed increased ankle dorsiflexion/plantarflexion, increased knee flex/extension, increased hip flex/extension, and increased knee abduction/adduction RoM angles when walking on the sand surface compared to the hard surface. Excessive coronal plane knee and ankle movement on a sand slant surface was observed. This indicates that walking on a sand slant surface may increase potential lower limb injury risk. MOLLE had a significantly increased hip abduction/adduction RoM angle over ALICE. This may be an indication of a higher risk hip injury potential in MOLLE.

Introduction

Modern soldiers often carry more equipment than ever before as more technological devices have been developed to aid and protect soldiers [1]. Over the last decade, extensive research has been done to evaluate the relationship between load carriage and military injuries [2-5] as well as load carriage and lower limb kinematic gait effects [6-9]. Two recent military studies were undertaken to increase knowledge about the effects of load carriage in military backpacks during marching. These studies proposed that the risk of injury due to substantial burden on the individual soldier's musculoskeletal system was associated with load carrying [10, 11]. The general result of the previous research is that the lower limb potential injury risk was increased as the load increased.

With the load carriage system, another important condition in gait kinematics is surface. Little research has been done investigating gait on irregular surfaces [12-14]. To the author's knowledge, at the time of this study, no research had been performed to investigate human locomotion on sand surface with load carriage. Transverse surface slope is also a crucial factor of increasing lower limb musculoskeletal injury risk [15]. Most of the research has been performed on level and hard surface conditions. Only a few studies have presented lower limb gait changes over transversely slanted slopes [14, 15 16]. Increased hip flexion/extension and knee flexion/extension angle on a slant condition have been shown previously [14]. Dixon and Pearsall (2003) also found similar results and explained those gait changes as the natural human body reaction on irregular surface conditions to reduce trips and falls [15].

The current research will primarily focus on investigating the kinematic changes on sand and transverse planes. This study also investigates the effect of two backpacks, MOLLE and ALICE, on a soldier's gait performance. The study results are expected to help formulate new guidelines for military operations on sand and transverse planes. These improved guidelines could aid in reducing the risk of noncombat military injuries for soldiers during training and service. We also would expect that the results will assist in investigations pertaining to soldiers' injuries and will be used to develop new equipment to reduce the stresses caused by heavy loads.

Method

Participants

Twenty healthy male participants participated in this study. Participants were selected from a healthy young population who meet the selection criteria of current military recruiting standard [17]. The participants' anthropometric data were measured and recorded, with a mean (±SD) age of 25.1±3.6 years, height of 175.6±64.6 cm, and body mass of 74.9±7.7 kg. All participants reviewed and signed an informed consent document approved by University of Utah Institutional Review Board.

Backpacks and Boots

Two dominant types of military backpacks in current use were selected; these were the ALICE and the MOLLE backpacks. The ALICE backpack is a military issue backpack consisting of a sack, aluminium frame, and various straps and supports. This backpack was adopted in 1973 and has been used until the MOLLE backpack was introduced in 2001. The MOLLE backpack is a standard for modular tactical gear, replacing the ALICE system used as an earlier load carriage system. The general marching load range established by U.S. forces is from 25.9kg to 32.7kg [18]. In this study, each backpack has the same load of 29kg (64lbs). This load includes initial backpack weight, all associated accessories, and other devices for data collection.

One type of U.S. Military boots was selected to minimize any bias error resulting from using different footwear types. The University of Utah Military Science department supported U.S. Army issued desert tan BELLEVILLE 790G Gore-Tex combat boots.

Tracks and Force Platforms

The current study used two customized tracks in order to replicate sand and hard surfaces, respectively, along with changes in transverse slope conditions. Five height adjustable hand cranks were installed on each side of the track to provide transverse slopes. The transverse slope angle that the current study required was 10°. The dimension of the track used is 0.76 m by 7.3 m.

One track was filled with sand to simulate a desert environment. A specific sand type was carefully selected under the guidance of a professor from the Geology department and a former resident of Iraq to best simulate the desert environment in the Middle Eastern region. The other track was covered with ¾ inch reinforced plywood to replicate a hard surface condition.

A total of 4 force plates, 2 (OR6-5-1000 & OR6-7, AMTI, Watertown, MA) for the sand surface and 2 (FP4060-08-1000, BERTEC, Columbus, OH) for the hard surface, were used to collect ground reaction data at a sampling rate of 2000 Hz. On the hard surface, participants contacted the force plates directly. The 2 force plates were isolated from each other and secured to reduce vibration before and after foot contacts. On the sand surface, these force plates were embedded under the sand and isolated by a customized isolation fixture that was originally designed by another researcher [14]. This customized isolation fixture was used to reduce the dissipation of force from surrounding sand. Merryweather (2008) confirmed that this force plate isolation technique could serve well to test railroad ballast as well as other surfaces [14].

Motion Capture System and Markers

3-D motion data were captured with 16 NatrualPoint V100:R2 cameras and AMASS software at a sampling rate of 100Hz. A custom data acquisition interface was designed with LabVIEW (National Instruments, Version 10.0.1) for force data at a sampling rate of 2000Hz. The captured data were further processed using Visual3D software (modelling) and Vicon Nexus software (trajectory postprocessing). For static trials, reflective markers were attached bilaterally to the participants at the following locations: anterior superior iliac spine, posterior superior iliac spine, lateral femoral condyle, medial femoral condyle, lateral malleolus, medial malleolus, calcaneus, between the second and third proximal metatarsal heads, and head of the 5th Metatarsus. In addition to the predefined marker set from C-motion, marker clusters were also used on thighs and shanks for static and dynamic tracking purposes. A static trial was captured for 6 seconds for each participant in order to calibrate the marker set and to create a model.

Protocol

The independent variables being controlled for in this study are: surface type (hard, sand), slope (flat, slant), backpack type (no load, MOLLE, ALICE), and marching speed (self-selected and 4 km/h). Each backpack weighed 29kg (64lbs) and the load was evenly distributed inside the backpack.

Participants were guided to walk at two different walking speeds. The marching speed of 4km/h was selected as the normal marching speed for foot troops based on the U.S. Army Field Manual 21-18 [19]. They were guided to follow the flag that was moving constantly at 4km/h at the participant's eye height. Self-selected speed was freely chosen by the participant as their normal walking speed. To minimize the learning effect by the forced marching speed, a randomized block design was used where the track (surface and slope) was the blocking parameter.

Participants were asked to walk down a 24 ft. walkway approximately 144 times. The total walking distance was projected to be approximately 0.67 miles and the total estimated time walking during the study was approximately 40 minutes. Right foot was always in downslope and left foot always in upslope. Two force plates measured the forces of each foot individually.

Markers were placed according to Visual3D guidelines provided by the C-Motion. These markers described the location of each body segment at any point in time for calculating joint positions, velocities, and accelerations. After the participant was equipped with the markers and every calibration initial preparation process was done, the participant was asked to walk down the track. After collecting 3 trials per condition, each participant was provided with enough recovery time to reduce the fatigue effect.

Additional force plate calibration measurements were taken each time the slope configuration was changed.

Data Analysis

The performance of the proposed model was evaluated using traditional statistical and epidemiological techniques. Key kinematic variables of gait analysis for this study were ankle, knee, and hip range of motion (RoM) angle.

Ankle, knee, and hip range of motion angle data were calculated from HS (heel strike) to HS and normalized by 101 data points as 0% at HS and 100% at HS. Hip and knee flexion/extension angle at HS and ankle flexion/extension angle at TO (toe off) were also measured.

3-D motion data were captured at a sampling rate of 100Hz. Video data and analog data were filtered with a cut-off frequency of 6 Hz using the function in Visual3D prior to further data analysis. Additionally, Ground reaction force data were divided by the body weight of each participant to normalize and acquire the percent body weight for easy comparison of data. Moments were also normalized using a normalizing function in Visual3D. Error bars in each bar graph represent standard deviation of the data.

Statistical Analysis

The repeated measures analysis of variance (RM ANOVA) method was used. All main effects were analyzed by comparing the following independent variables: surface type, slope, walking speed, and backpack type. All two-way interaction effects were also analyzed. The significance level was set at 0.05. Post-hoc tests were conducted using Tukey LSD to run the pairwise comparison for load types. The statistical tests were performed using SPSS 18.0 for Windows (IBM Corporation, Armonk, NY).

Results

Surface Effect

Several statistically significant differences were found between hard and sand surfaces: ankle dorsi/plantarflexion RoM ($p<0.001$), knee flexion/extension RoM ($p<0.001$), hip flexion/extension RoM ($p<0.001$), and knee valgus/varus RoM ($p<0.001$). The results are shown in Figure 4-1, Figure 4-2, Figure 4-3, and Figure 4-4.

Slope Effect

It was found that the effect of slope was significant for the ankle dorsi/plantarflexion RoM, knee flex/extension RoM, hip flex/extension RoM, ankle in/eversion RoM, knee valgus/varus RoM, and hip ab/adduction RoM. The resulting summary of *p* values and post-hoc test results are shown in Table 4-1. Values for these parameters are described in Figure 4-1, Figure 4-2, Figure 4-3, Figure 4-5, Figure 4-4, and Figure 4-6.

Surface × Slope Effect

The ankle dorsi/plnatarflexion RoM, knee flexion/extension RoM, and hip flexion/extension RoM were found to be significantly different by surface and slope interaction ($p=0.001$, $p<0.001$, and $p<0.001$). Figure 4-1, Figure 4-2, and Figure 4-3 describe the associated values. Kinematic curves by surface and slope interaction effects for ankle, knee, and hip RoM angles are described in Figure 4-7, Figure 4-8, and Figure 4-9.

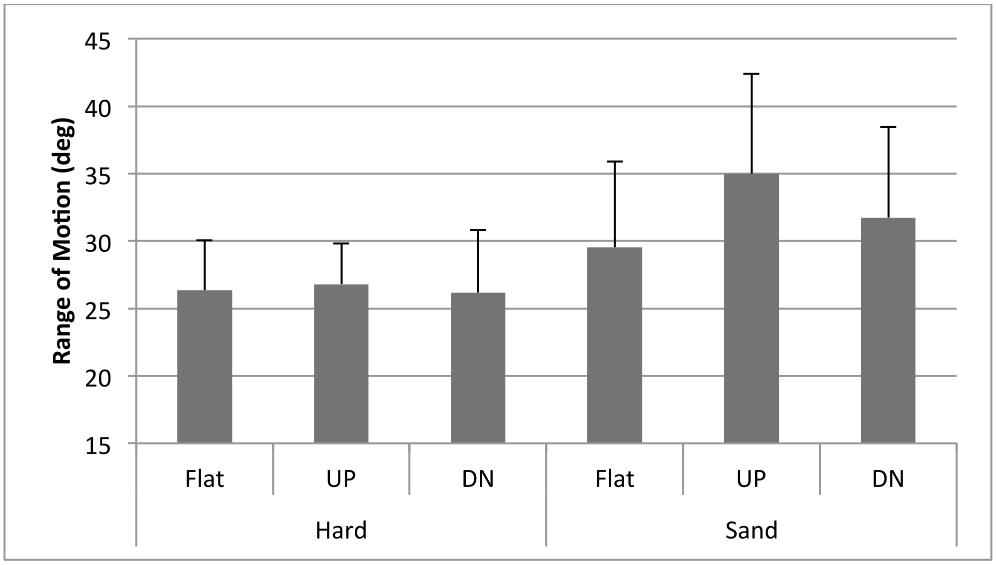

Figure 4-1. Ankle Dorsi/Plantarflexion RoM by Surface and Slope (*p*<0.001)

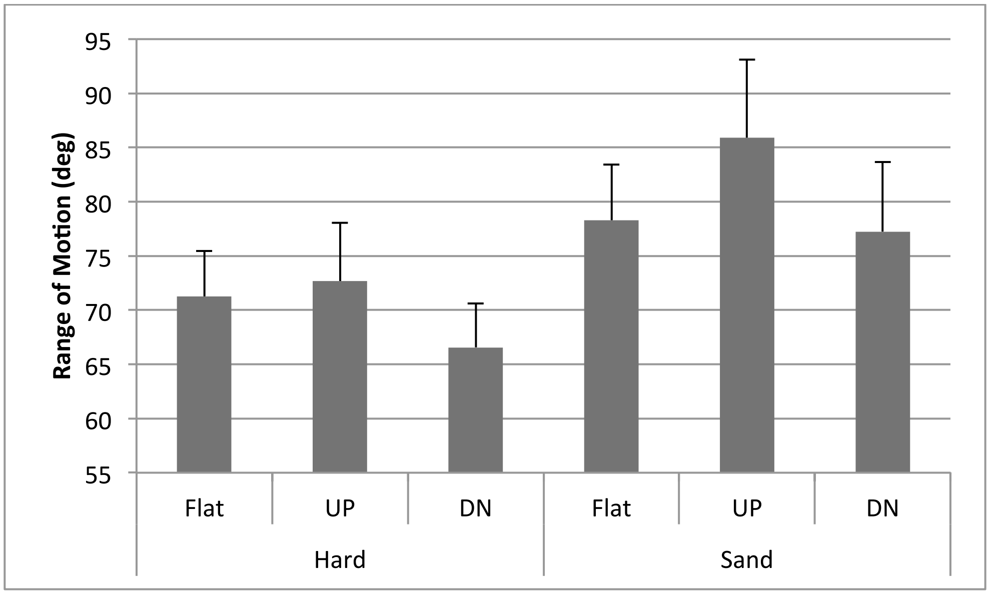

Figure 4-2. Knee Flexion/Extension RoM by Surface and Slope (*p*<0.001)

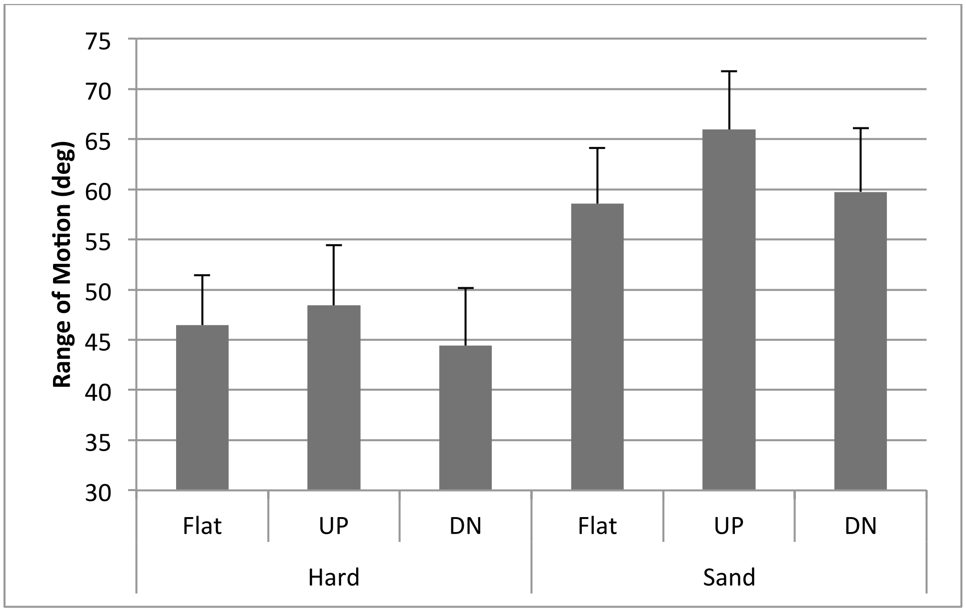

Figure 4-3. Hip Fexion/Extension RoM by Surface and Slope ($p<0.001$)

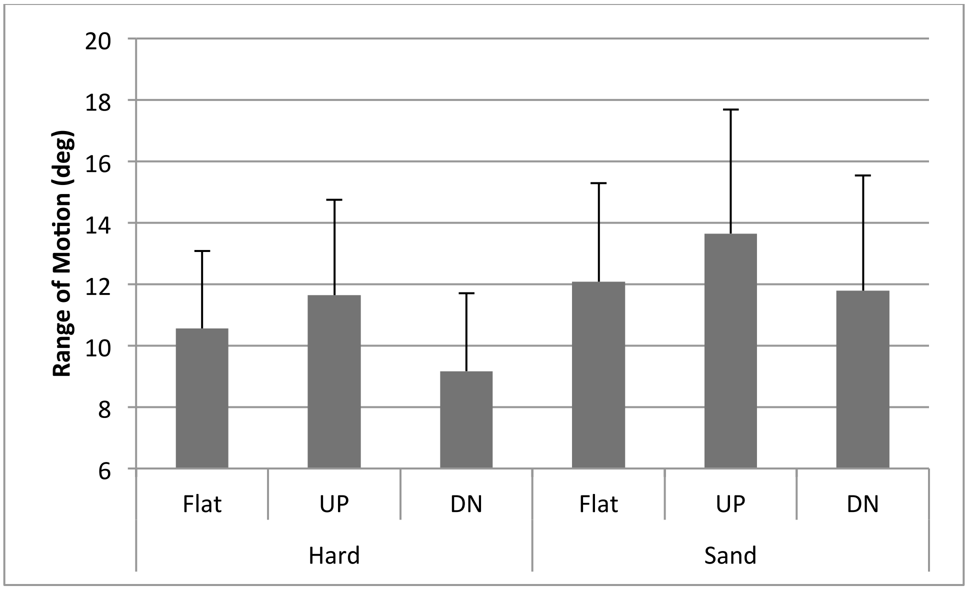

Figure 4-4. Knee Valgus/Varus RoM by Surface and Slope ($p<0.001$)

Table 4-1. Summary of the main and post-hoc slope effects

		Significant Effect	Post-hoc		
			Flat vs. UP	Flat vs. DN	UP vs. DN
Ankle	Dorsiflexion/Plantarflexion	Yes	**0.000**	0.106	**0.032**
	Inversion/Eversion	Yes	**0.000**	**0.049**	**0.000**
	Rotation	Yes	**0.000**	0.563	**0.000**
Knee	Flexion/Extension	Yes	**0.000**	**0.000**	**0.000**
	Valgus/Varus	Yes	**0.000**	**0.001**	**0.000**
	Rotation	No	0.139	0.083	0.932
Hip	Flexion/Extension	Yes	**0.000**	0.535	**0.000**
	Abduction/Adduction	Yes	**0.000**	**0.000**	**0.000**
	Rotation	Yes	**0.021**	0.118	**0.033**

Note: Numbers in the table represent *p* values.

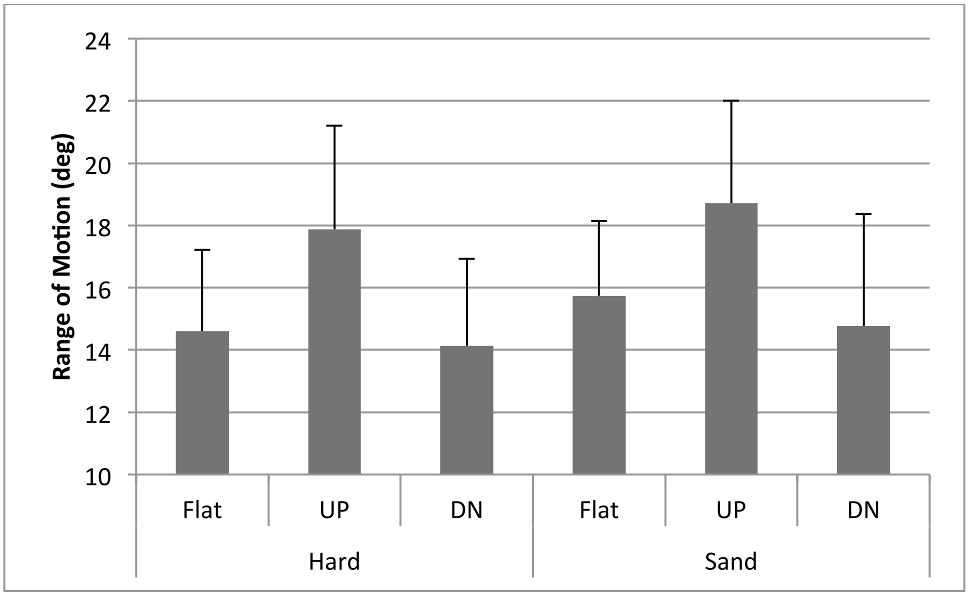

Figure 4-5. Ankle Inversion/Eversion RoM by Surface and Slope (*p*<0.001)

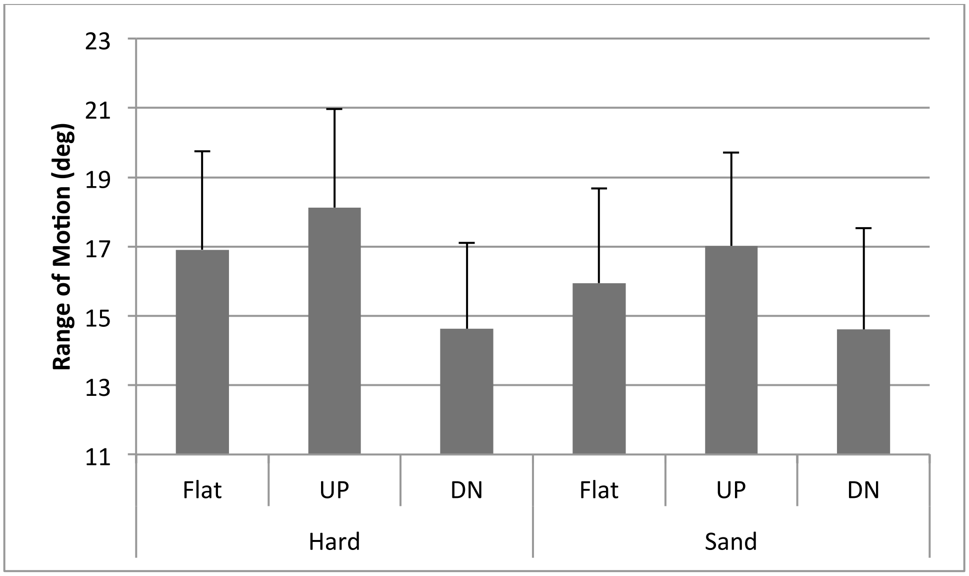

Figure 4-6. Hip Abduction/Adduction RoM by Surface and Slope (*p*=0.017)

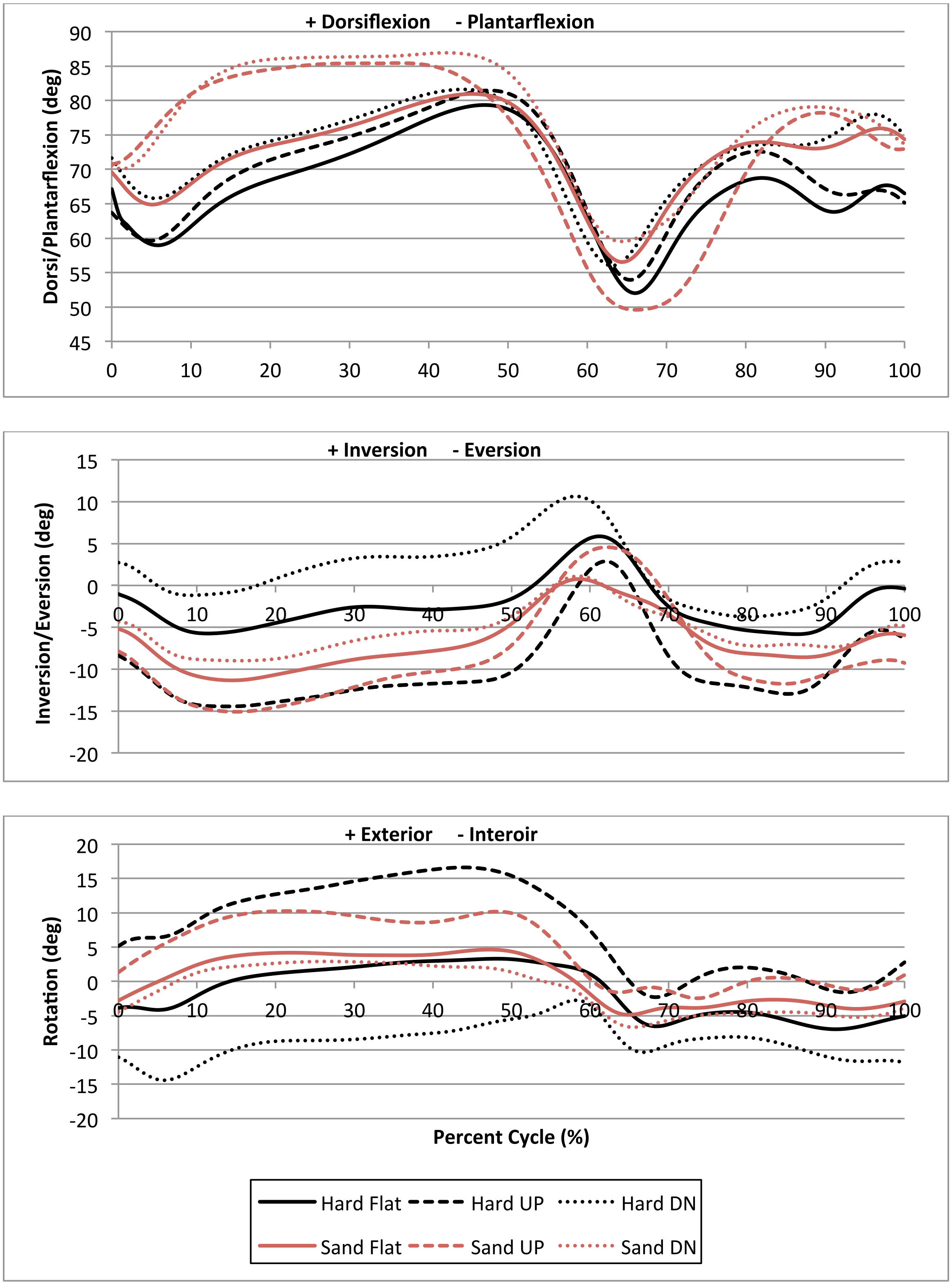

Figure 4-7. Ankle Kinematics by Surface and Slope

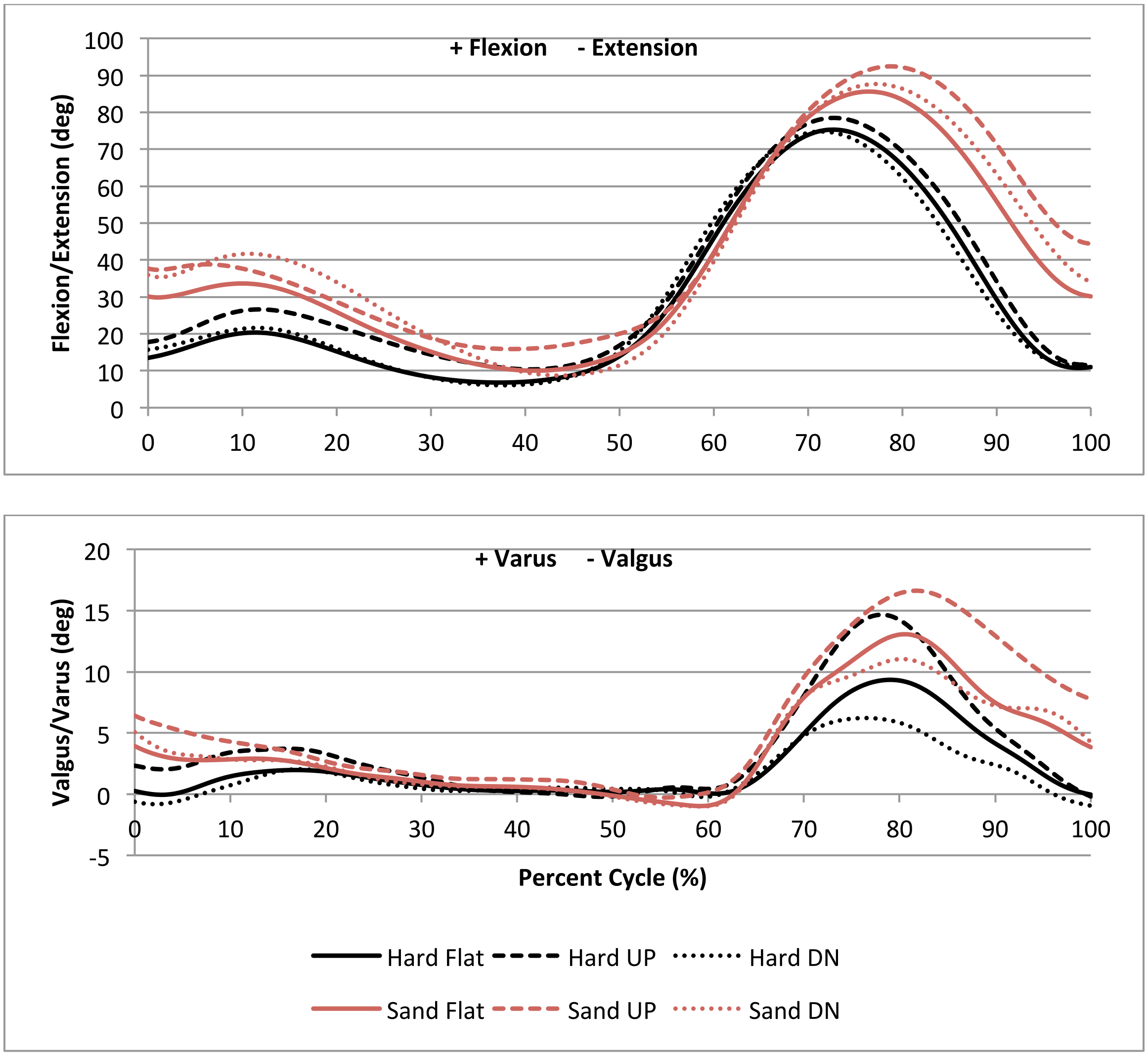

Figure 4-8. Knee Kinematics by Surface and Slope

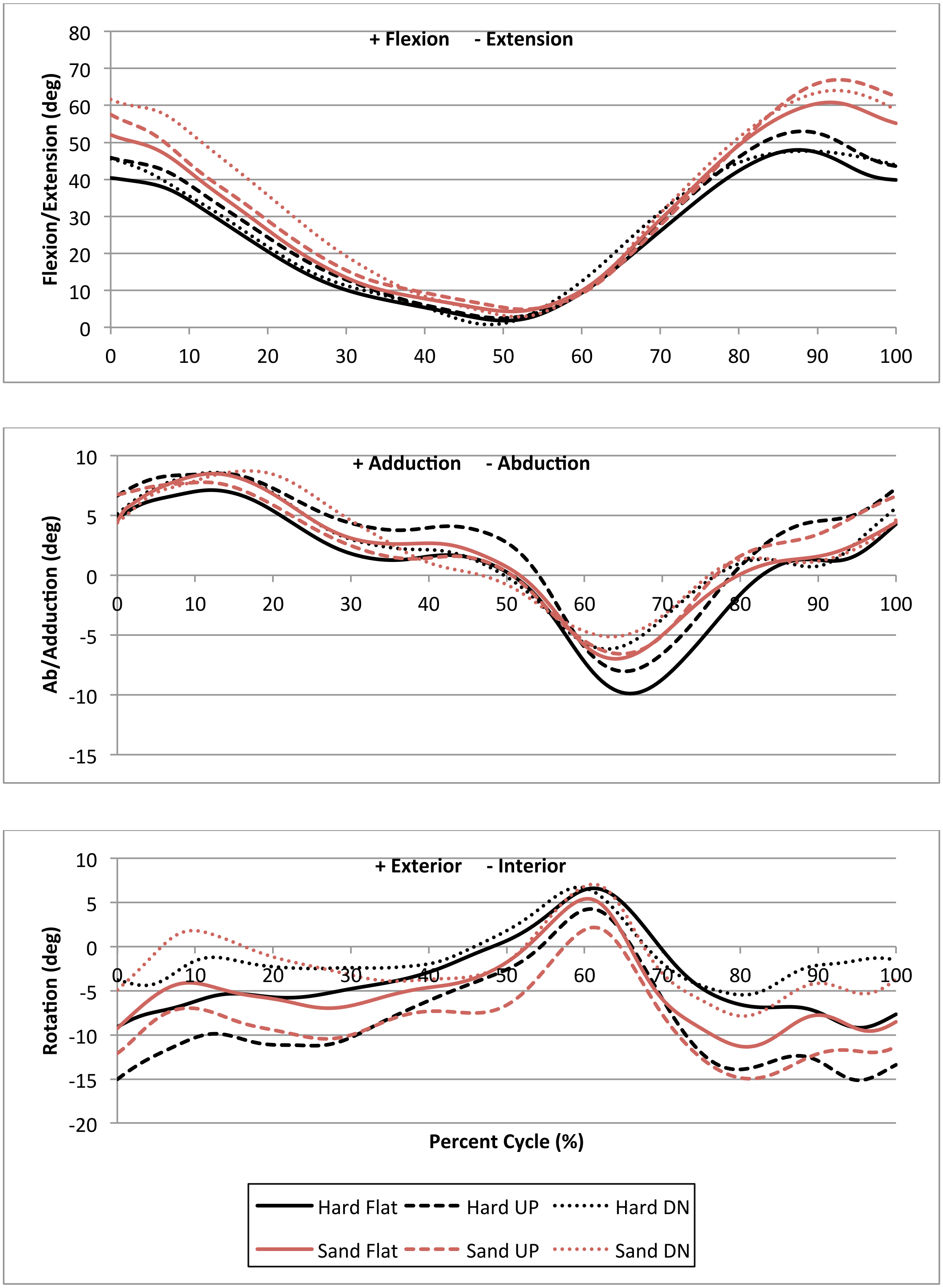

Figure 4-9. Hip Kinematics by Surface and Slope

Backpack Effect

There were statistically significant effects among load conditions in all 9 variables. A backpack changed the ankle, knee, and hip RoM significantly. Post-hoc test results also were shown in Table 4-2. The results are described in Figure 4-10, Figure 4-11, and Figure 4-12. Kinematic curves for ankle, knee, and hip RoM angle by backpack effects are shown in Figure 4-13, Figure 4-14, and Figure 4-15.

Backpack × Surface Effect

Ankle flexion/extension RoM and knee flex/extension RoM had statistically significant interaction effects by backpack and surface ($p<0.001$, $p=0.001$). Values are described in Figure 4-16 and Figure 4-17.

Backpack × Slope Effect

Knee valgus/varus RoM angle and hip abduction/adduction RoM angle showed statistically significant interaction effects by backpack and slope ($p=0.016$ and $p=0.031$). The results are described in Figure 4-18 and Figure 4-19.

Discussion

The current study showed that the ROM of ankle dorsi/plantarflexion, knee flexion/extension, and hip flexion/extension angles increased on a sand surface as compared to a hard surface. The RoM of each joint angle in the sagittal plane were increased on an uphill, compared to a flat surface [15, 16, 20-22]. This increase was more noticeable on a sand surface and the increment was greater than on a hard surface;

Table 4-2. Summary of the main and post-hoc backpack effects

		Significant Effect	Post-hoc		
			No vs. MOLLE	No vs. ALICE	MOLLE vs. ALICE
Ankle	Dorsiflexion/Plantarflexion	Yes	**0.000**	**0.000**	**0.004**
	Inversion/Eversion	Yes	**0.000**	**0.000**	**0.025**
	Rotation	Yes	**0.000**	**0.000**	0.152
Knee	Flexion/Extension	Yes	0.132	**0.024**	0.112
	Valgus/Varus	Yes	0.129	**0.022**	**0.050**
	Rotation	Yes	**0.000**	**0.000**	0.372
Hip	Flexion/Extension	Yes	**0.000**	**0.000**	0.159
	Abduction/Adduction	Yes	**0.007**	0.908	**0.001**
	Rotation	Yes	**0.018**	**0.000**	0.165

Note: Numbers in the table represent *p* values.

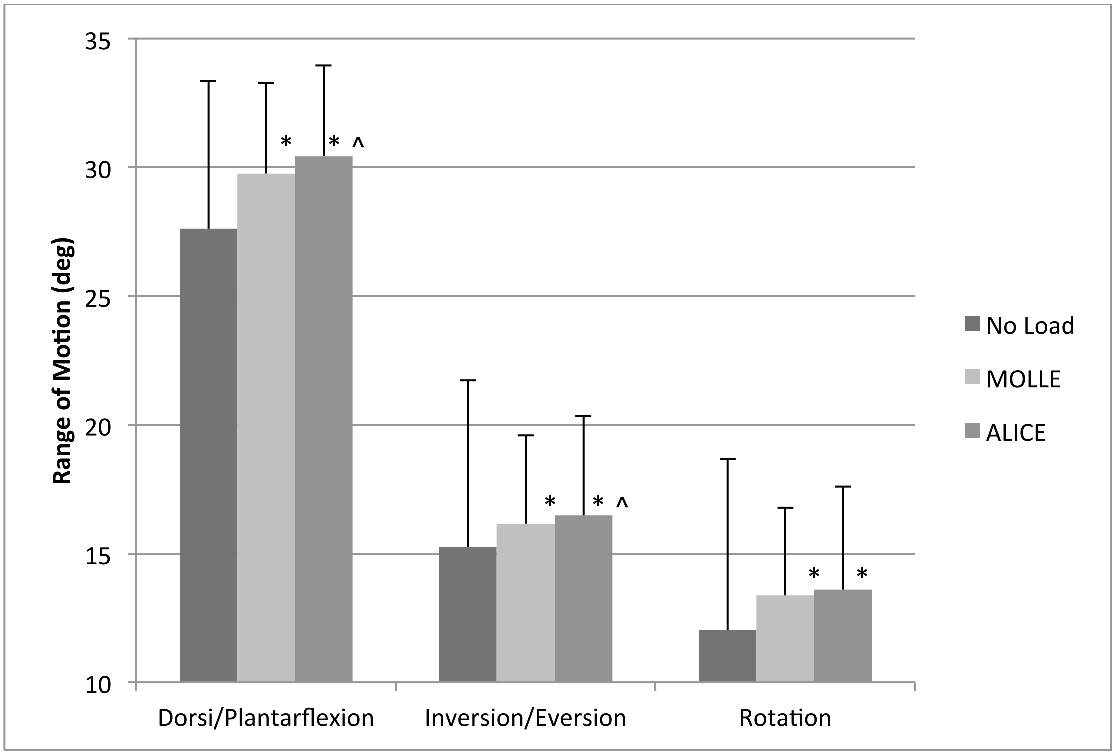

Figure 4-10. Ankle RoM Angle by Load Types
* indicates statistical significance ($p<0.05$) compared to No Load. ^ indicates statistical significance ($p<0.05$) compared to MOLLE.

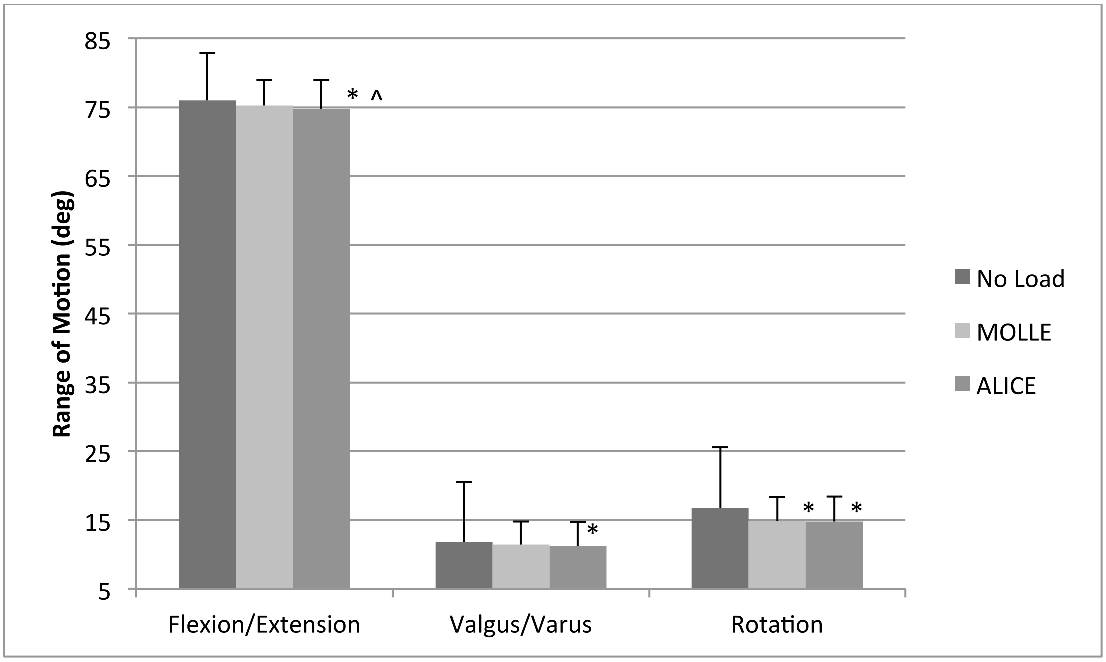

Figure 4-11. Knee RoM Angle by Load Types.
* indicates statistical significance ($p<0.05$) compared to No Load. ^ indicates statistical significance ($p<0.05$) compared to MOLLE.

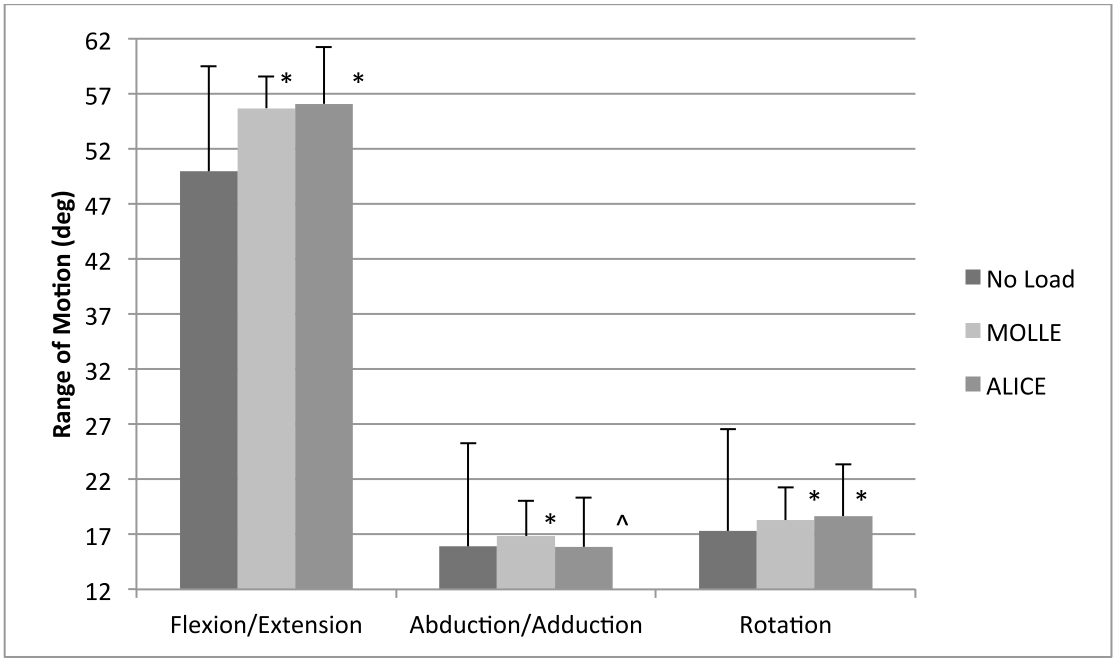

Figure 4-12. Hip RoM Angle by Load Types
* indicates statistical significance ($p<0.05$) compared to No Load. ^ indicates statistical significance ($p<0.05$) compared to MOLLE.

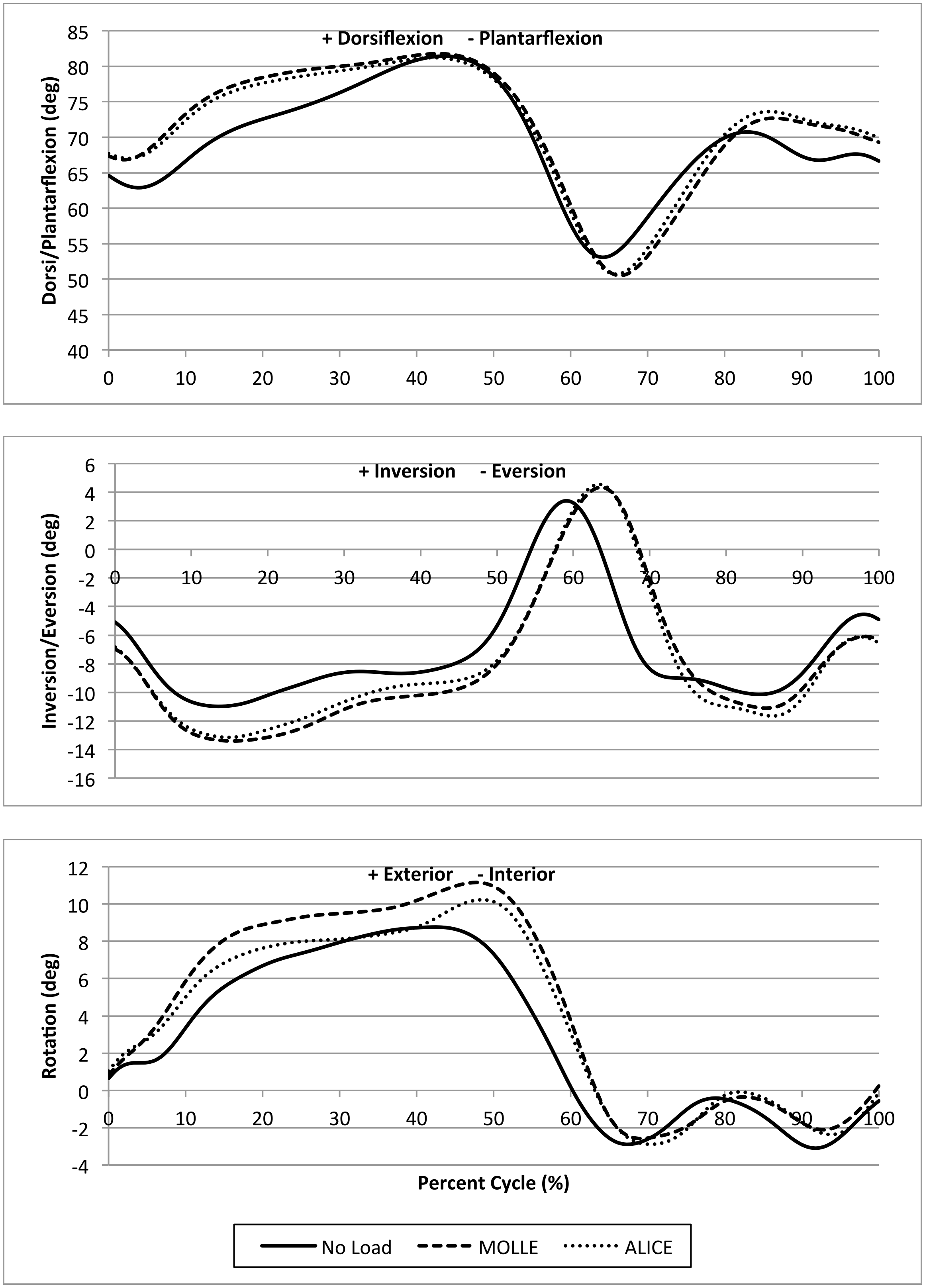

Figure 4-13. Ankle Kinematics by Backpack

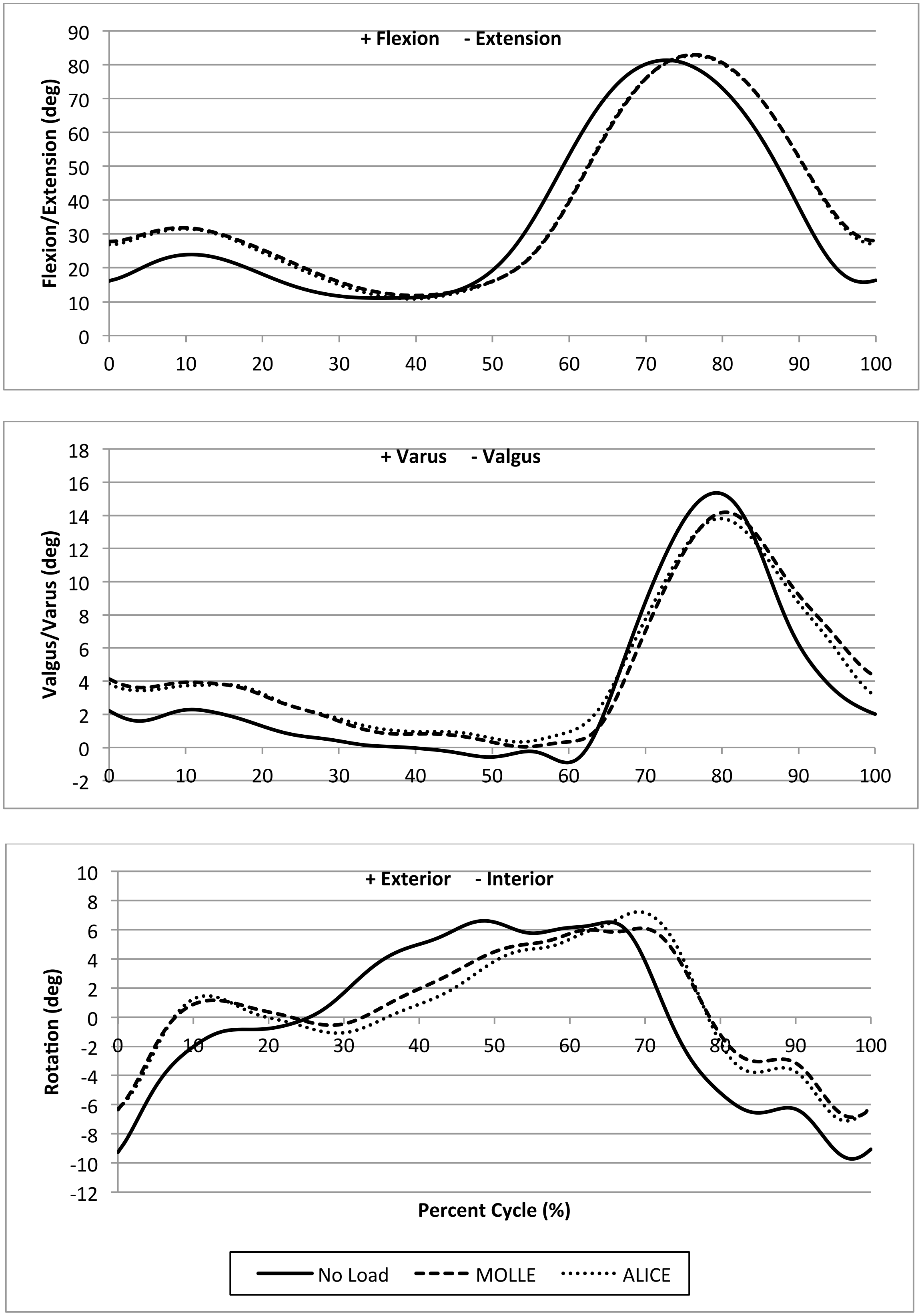

Figure 4-14. Knee Kinematics by Backpack

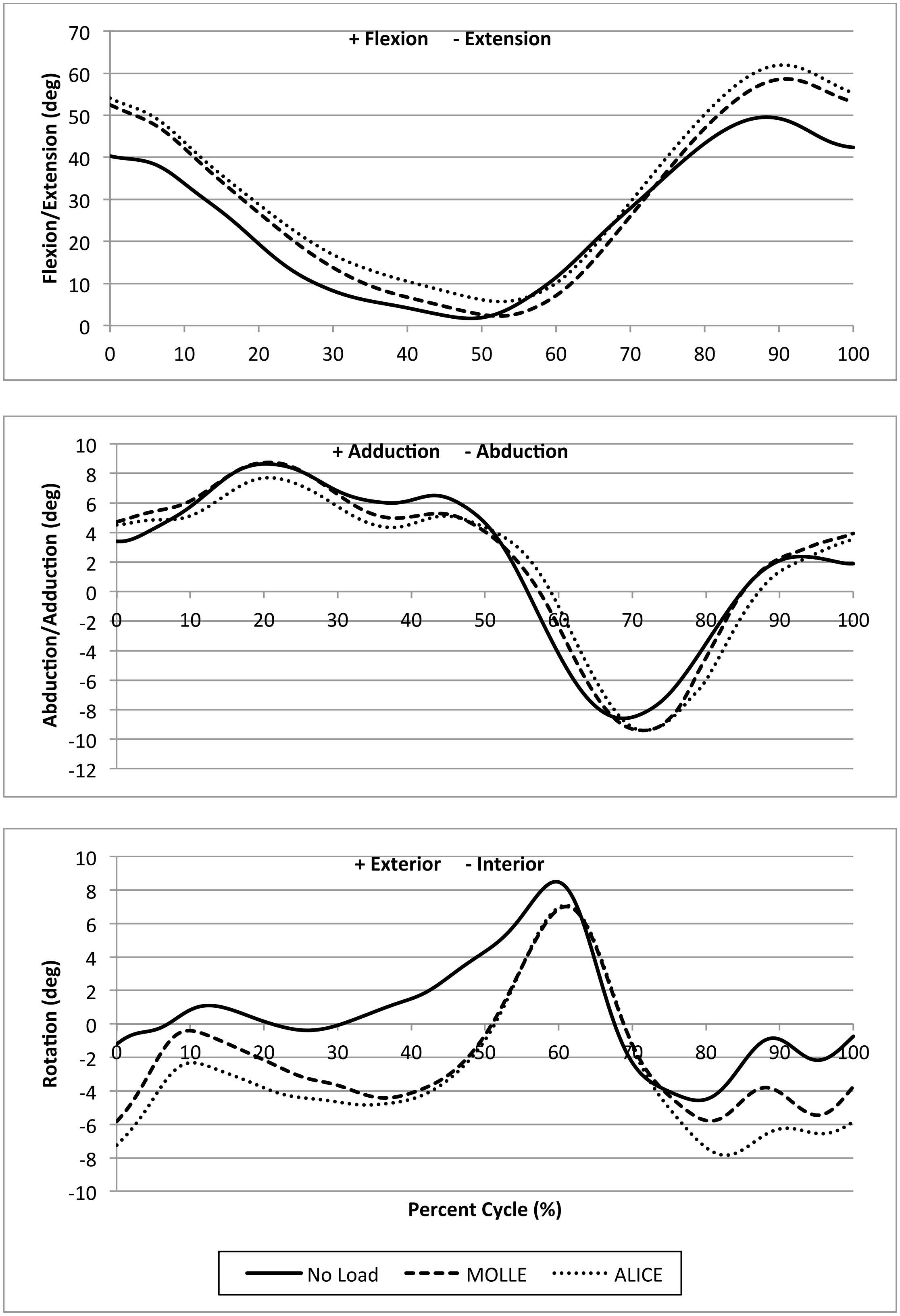

Figure 4-15. Hip Kinematics by Backpack

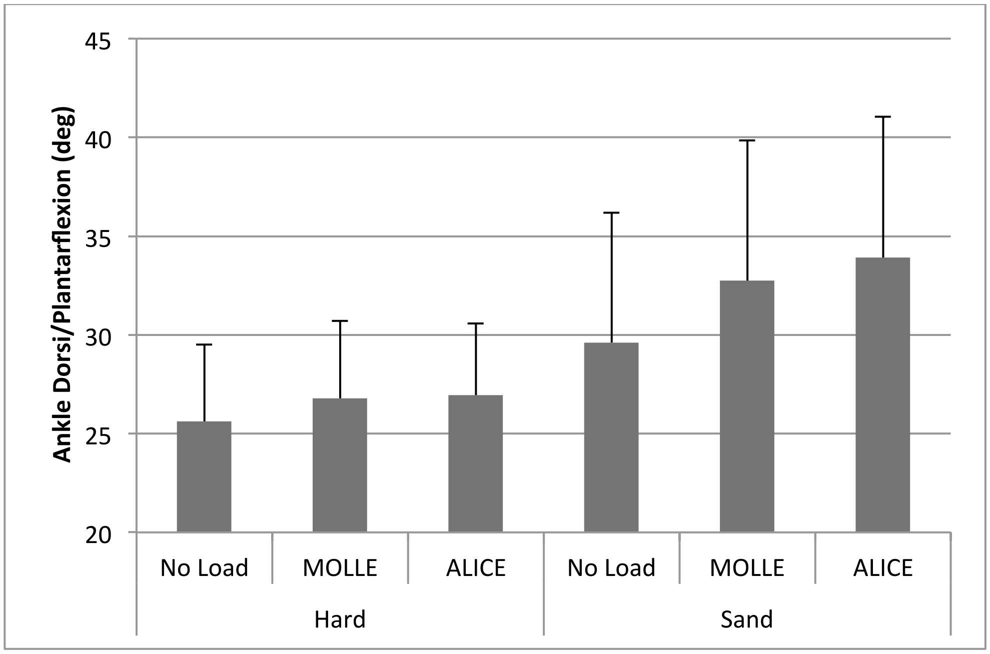

Figure 4-16. Ankle Dorsi/Plantarflexion RoM Angle by Backpack × Surface (p<0.001)

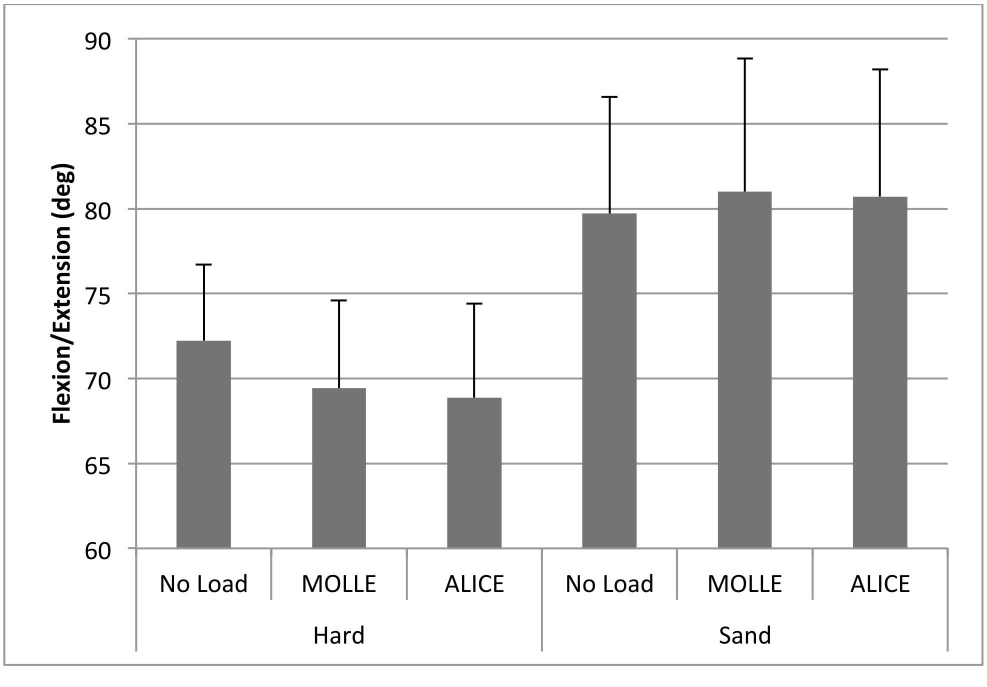

Figure 4-17. Knee Flexion/Extension RoM Angle by Backpack × Surface (p=0.001)

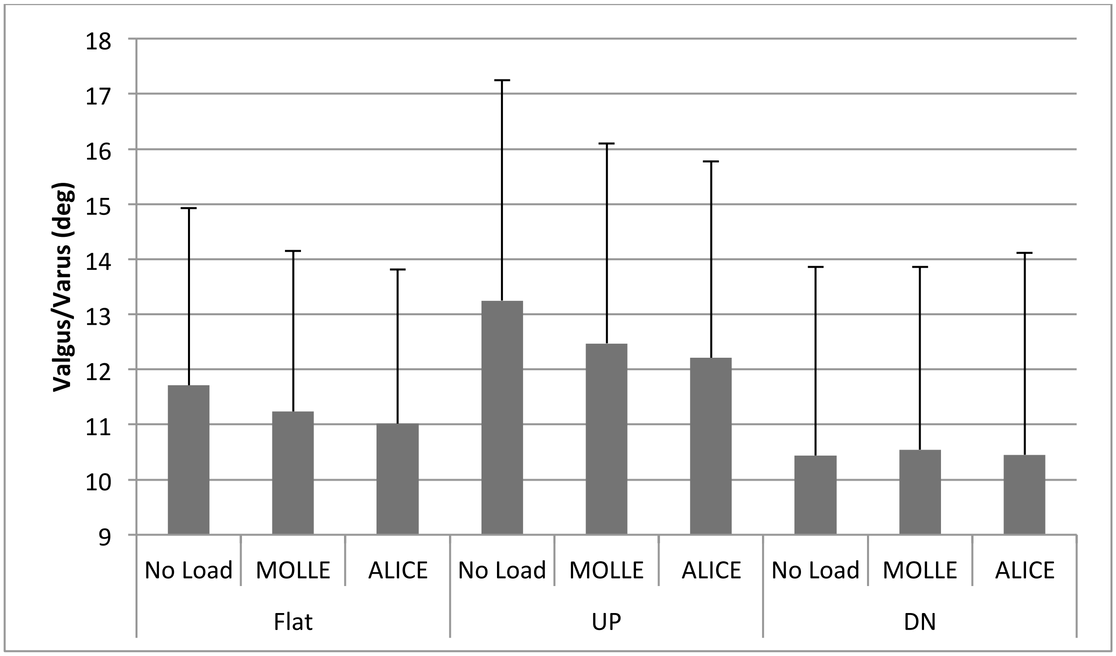

Figure 4-18. Knee Valgus/Varus RoM Angle by Backpack × Surface (*p*=0.016)

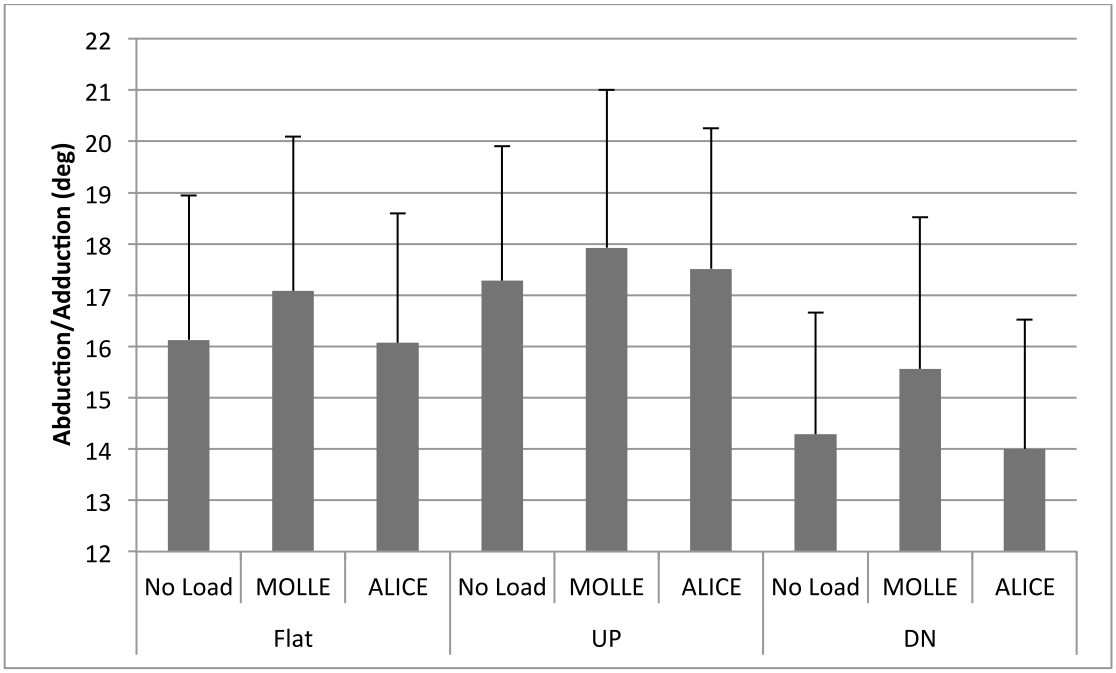

Figure 4-19. Hip Ab/Adduction RoM Angle by Backpack × Surface (*p*=0.031)

however, during downhill walking, the RoM of these joints were inconsistent across the joints [22]. An increase in knee flexion is necessary to raise the limb to provide sufficient foot clearance. This increase was observed during the early-to-mid swing phase.

Knee flexion/extension RoM was greater for the sand surface than for the hard surface and for the uphill more than the flat surface. With the added load, knee flexion/extension RoM angle decreased for the hard surface. The decreased knee flexion angle was maintained throughout the gait cycle for the hard surface. However, knee flexion/extension RoM angle increased with added load for the sand surface. Also increased knee flexion angle with added load was observed at heel strike for both hard and sand surfaces. An increase in knee flexion at heel strike with added load is a preparation mechanism as a shock absorber for the impact force [6]. High impact forces are a major risk factor for overuse injuries in military [11]. Overuse injuries, often referred to as heavy load injuries, are very common and constitute a large percentage of military injuries [4, 23]. On the sand surface, walking on this surface with added load required increased knee flexion/extension RoM angle compared to hard surface.

Increased hip flexion/extension RoM for the uphill and for the sand surface was also investigated to follow the mechanism to raise the leg up to avoid an obstacle. This increased hip RoM trend was also observed at HS for the uphill limb. The sand surface created increased ankle dorsiflexion in comparison to a hard surface. The effort of standing the body up vertically by shortening the uphill leg length while walking on the sand surface requires more energy than walking on a hard surface [24].

In the coronal plane, ankle inversion/eversion RoM angle was greater on the sand uphill surface compared hard flat surface. The excessive coronal plane ankle movement caused by a slant surface could increase the risk of ankle ligament injury [15]. The unstable sand slant surface condition makes the medial lateral ankle complex injury risk even higher [15, 25]. Other researchers also confirmed that the excessive dorsi/plantarflexion of foot could also be potential factors of lower limb injuries [26].

Apart from other research, the current research found decreases in lateral knee movement and rotation as the backpack was carried [6]. The decrease in medial/lateral and rotational movement could be interpreted as the locking mechanism to maintain the lower body stable from excessive movement. There was also a greater difference in ankle dorsi/plantarflexion on sand surfaces when a load was carried. The depth of the imprint on sand surface with added load was greater and as a result, it required more knee movement in the sagittal plane to clear the surface during swing [27]. Greater ankle movement in the sagittal plane requires more force to push off the sand and thereby increases the risk of metatarsalgia [24, 28].

Some notable differences were found between the two backpacks, MOLLE and ALICE. There was a significant main effect for an increased hip abduction/adduction RoM angle in MOLLE than ALICE. A mild pain in the hip due to an excessive hip RoM during load carriage was observed from other research [4, 29]. Although the difference is relatively small, it may increase the significance for the military soldiers because they tend to walk for a longer period of time in several days in some cases (MOLLE is 16.9° and ALICE is 15.9°).

Conclusion

This study produced several kinematic parameters of note during walking on a sand surface vs. a hard surface, including increased ankle dorsi/plantarflexion, knee flex/extension, hip flex/extension, and knee abduction/adduction RoM. The effort of keeping the body balanced on a sand surface by increasing joint movement in the sagittal plane makes walking on a sand surface more difficult. The excessive coronal plane knee and ankle movement on a sand slant surface could potentially increase the risk of ankle and knee injury.

As evidenced by the results, increased load is a major factor in injury development. Increased ankle dorsi/plantarflexion and hip flex/extension RoM angle were observed during added load for both the sand and the hard surfaces. However, knee flex/extension revealed more divergent kinematics on each surface; increased knee RoM on the sand surface was observed to avoid surface obstacles by lifting the leg up; but decreased knee RoM on the hard surface was observed to maintain stability of the leg and body during gait cycle. The main goal for injury reduction should therefore be primarily focused on reducing the backpack weight by developing lightweight backpack material and by using lightweight accessories, such as a helmet, body armour, a rifle, and a respirator.

Of the two backpacks, only MOLLE had a statistically significant increase in hip abduction/adduction RoM. Increased hip movement in the frontal plane indicates a high risk of hip injury. Although the difference is relatively small and the exact injury mechanism cannot be explained, soldiers who are carrying the MOLLE backpack and are performing prolonged road marching operations may be exposed to a higher risk for hip overuse injuries than those carrying the ALICE backpack.

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CHAPTER 5

THE EFFECT OF CARRYING A MILITARY BACKPACK ON A TRANSVERSE SLOPE AND SAND SURFACE ON LOWER LIMB KINETIC PARAMETERS DURING GAIT

Abstract

The objective of this study is to understand gait kinetics while walking on sand surfaces and to investigate the differences between gaits while wearing a MOLLE and an ALICE backpack. A mean M/L GRF increase was observed as the load was added. The mean M/L GRF was greater on the sand surface compared to the hard surface. Gait on sand surfaces also had a greater maximum vertical impact force, which could be the main contributing factor for overuse injuries of lower extremities. The sand surface also had a greater mean knee abduction/adduction moment. On the hard surface, however, increased the maximum vertical thrust forces, increased maximum braking forces, and increased maximum propulsive forces were observed and they could be the cause of increased foot strain and foot blisters.

With the added load, the mean hip ab/adduction moment was greater for the ALICE than for the MOLLE. The trend toward increasing the mean hip ab/adduction moment for ALICE was also investigated from the backpack/surface interaction and the

backpack/slope interaction effects.

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 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 is therefore 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]. Stefanyshyn, et al. (2006) proposed that high patellofermoral 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.

Method

Participants

Twenty healthy male participants volunteered for this study (age 25.1 ± 3.6 years, height 175.6 ± 4.6 cm, mass 74.9 ± 7.7 kg). Participants were carefully selected from a healthy young population who fit to the current military soldiers' recruiting standard. The military anthropometric selection criteria were set at the following: age of 18 - 30, height of 161 - 195 cm, and mass of 55 - 87 kg [26]. All participants reviewed and signed an informed consent document approved by University of Utah Institutional Review Board.

Backpacks and Boots

Two current military backpacks, ALICE and MOLLE, were selected. The ALICE backpack is a military issue backpack consisting of a sack, aluminium frame, and various straps and supports. The MOLLE backpack is used to define the current generation of load-bearing equipment and it is modularized with compatible pouches and accessories. It is a standard for modular tactical gear, replacing the ALICE system used as an earlier load carriage system.

The standard backpack load carriage system varies by operation; however, the general marching load range is from 25.9kg to 32.7kg [27]. In this study, each backpack has the same load of 29kg (64lbs). This load includes initial backpack weight, all associated accessories, and other devices for data collection. The dimension of the MOLLE backpack is 24×32×62 (cm^3) and the ALICE backpack is 23×31×48 (cm^3).

The University of Utah Military Science department provided the currently using U.S. Army issued desert tan BELLEVILLE 790G Gore-Tex combat boots. Only one style of U.S. Military boots was worn to minimize any bias error resulting from using different footwear types.

Tracks and Force Platforms

Two customized tracks were used representing sand and hard surfaces respectively. Five height adjustable hand cranks were installed on each side of the track to provide transverse slopes of 10°. The dimension of the track used is 0.76 m by 7.3 m. One track was filled with sand to simulate a desert environment. A specific sand type was carefully selected under the guidance of a professor from the Geology department and a former resident of Iraq to best simulate the desert environment in the Middle Eastern region. The other track was covered with ¾ inch reinforced plywood to replicate a hard surface condition.

A total of 4 force plates, 2 (OR6-5-1000 & OR6-7, AMTI, Watertown, MA) for the sand surface and 2 (FP4060-08-1000, BERTEC, Columbus, OH) for the hard surface, were used to collect ground reaction data at a sampling rate of 2000 Hz. On the hard surface, participants contacted the force plates directly. Two force plates were isolated from each other and secured to reduce vibration before and after foot contacts. On the sand surface, force plates were embedded under the sand and isolated by a customized isolation fixture that was originally designed by another researcher [25]. This customized isolation fixture was designed to reduce the dissipation of force.

Motion Capture System and Markers

Three-dimensional motion data were captured with 16 NatrualPoint V100:R2 cameras and AMASS software at a sampling rate of 100Hz. A custom data acquisition interface was designed with LabVIEW (National Instruments, Version 10.0.1) for force data at a sampling rate of 2000Hz. The captured data were further processed using Visual3D software (modelling) and Vicon Nexus software (trajectory postprocessing).

For static trials, reflective markers were attached bilaterally to the participants at the following locations: anterior superior iliac spine, posterior superior iliac spine, lateral femoral condyle, medial femoral condyle, lateral malleolus, medial malleolus, calcaneus, between the second and third proximal metatarsal heads, and head of the 5th metatarsus. Marker clusters were also used on thighs and shanks for dynamic tracking purposes.

Protocol

The independent variables being controlled for in this study are: surface type (hard, sand), slope (flat, slant), backpack type (no load, MOLLE, ALICE), and marching speed (self-selected, 4 km/h). Each backpack weighed 29kg (64lbs) and the load was evenly distributed inside the backpack. Self-selected speed was chosen by the participant as their normal walking speed. The marching speed of 4km/h was selected based on the U.S. Army Field Manual 21-18 [1]. Participants were guided to follow the flag that was moving constantly at 4km/h.

Markers were placed according to Visual3D guidelines provided by the C-Motion. These markers described the location of each body segment at any point in time for calculating joint positions, velocities, and accelerations. After the participant was equipped with the markers and every calibration initial preparation process was done, the participant was asked to walk down the track. Both static and dynamic trials were captured for 6 seconds. Participants were provided with enough recovery time before the next set of trials to reduce the fatigue effect. Additional force plate calibration measurements were taken each time the surface type and slope was changed. A randomized block design was used, where the track (surface and slope) was the blocking parameter, meaning all necessary trials were performed for that specific blocked condition.

Data Analysis

The performance of the proposed model was evaluated using traditional statistical and epidemiological techniques. Key kinetic variables of gait analysis for this study were ground reaction forces and joint moments.

GRF data were sampled at 2000Hz. GRFs were further divided by M/L (medial and lateral), vertical, and anterior/posterior forces. 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 in this chapter. Maximum braking/propulsive forces, which could be measured anterior/posterior directional forces, were also investigated. Data were normalized by 101 data points as 0% at HS and 100% at HS. Knee abduction/adduction moments and hip abduction/adduction moments were selected as they have been reported as major injury components of gait.

3-D motion data were captured at a sampling rate of 100Hz. Video data and analog data were filtered with a cut-off frequency of 6 Hz using the function in Visual3D prior to further data analysis. Additionally, Ground reaction force data were divided by the body weight of each participant to normalize and to acquire the percent body weight for easy comparison of data. Moments were also normalized using a normalizing function in Visual3D. Error bars in each bar graph represent standard deviation of the data.

Statistical Analysis

Data were compared for the following variables: surface type (sand vs. hard), slope (0 vs. 10°), walking speed (self-selected vs. 4km/h), and backpack type (no load vs. MOLLE vs. ALICE) using the repeated measures analysis of variance (RM ANOVA). The significance level was set at 0.05. Post-hoc tests were conducted using Tukey LSD to run the pairwise comparison. The statistical tests were performed using SPSS 18.0 for Windows (IBM Corporation, Armonk, NY).

Results

Surface Effect

Several statistically significant differences were found between hard and sand surfaces: maximum vertical impact force, maximum vertical thrust force, mean M/L GRF, maximum braking force, maximum propulsive force, and mean knee A/A moment (p<0.001, p<0.001, p<0.001, p=0.001, p<0.001, and p=0.015). The results are shown in Figure 5-1, Figure 5-2, Figure 5-3, Figure 5-4, Figure 5-5, and Figure 5-6.

Slope Effect

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. A summary of the main and post-hoc kinetic effects is shown in Table 5-1. Values for these parameters are described in Figure 5-1, Figure 5-2, Figure 5-3, Figure 5-4, and Figure 5-7.

Surface × Slope Effect

The maximum vertical thrust force, mean M/L GRF force, maximum propulsive force, and mean hip A/A moment and were found to be statistically significant by surface and slope interaction (p<0.001, p=0.021, p=0.027, and p<0.001). Figure 5-2, Figure 5-3, Figure 5-5, and Figure 5-7 describe the values, respectively. Forces and moments for continuous curves by surface and slope interaction effects are described in Figure 5-8 and Figure 5-9.

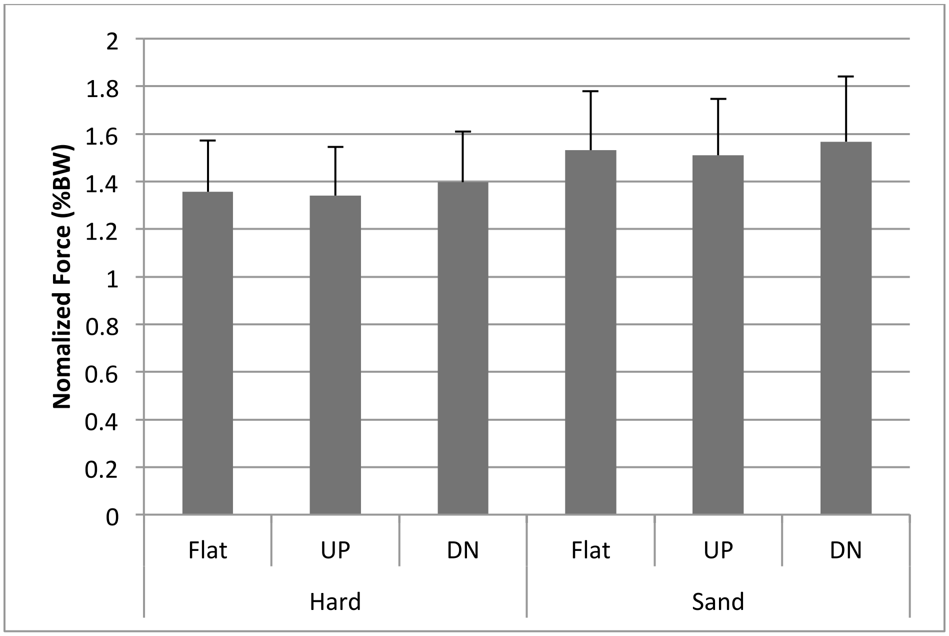

Figure 5-1. Maximum Vertical Impact Force by Surface and Slope ($p<0.001$)

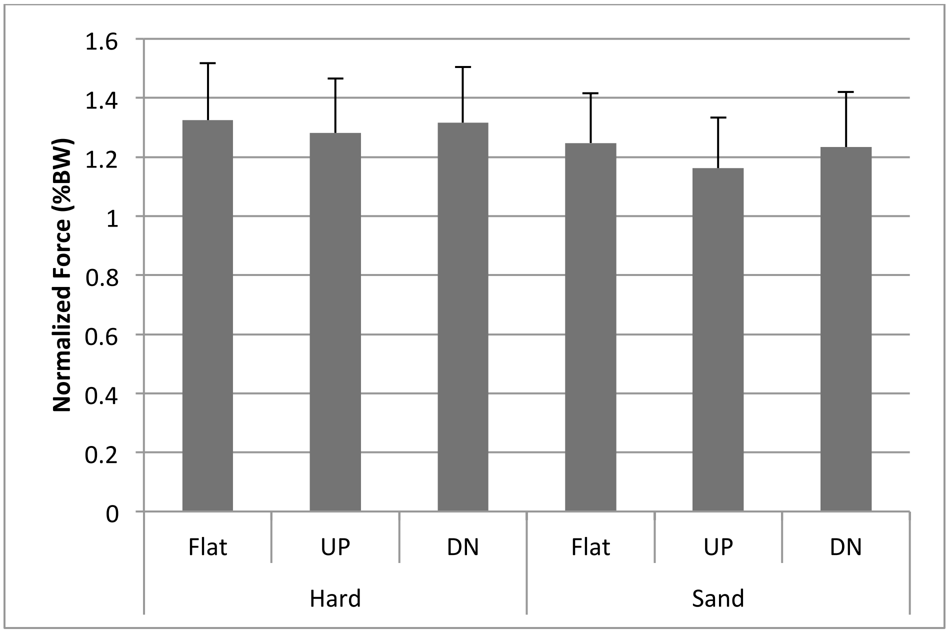

Figure 5-2. Maximum Vertical Thrust Force by Surface and Slope ($p=0.021$)

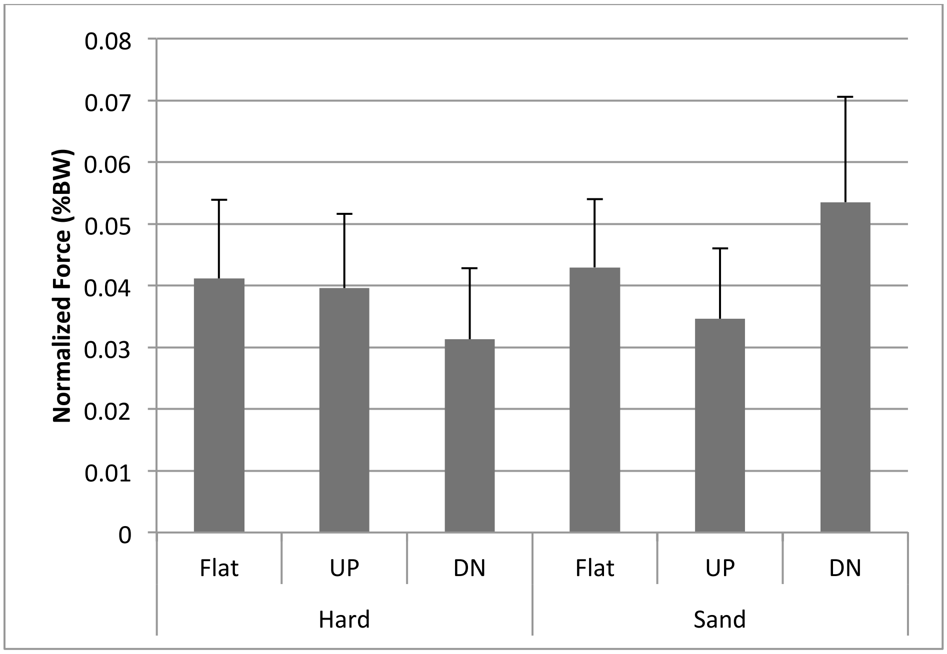

Figure 5-3. Mean M/L GRF by Surface and Slope (*p*<0.001)

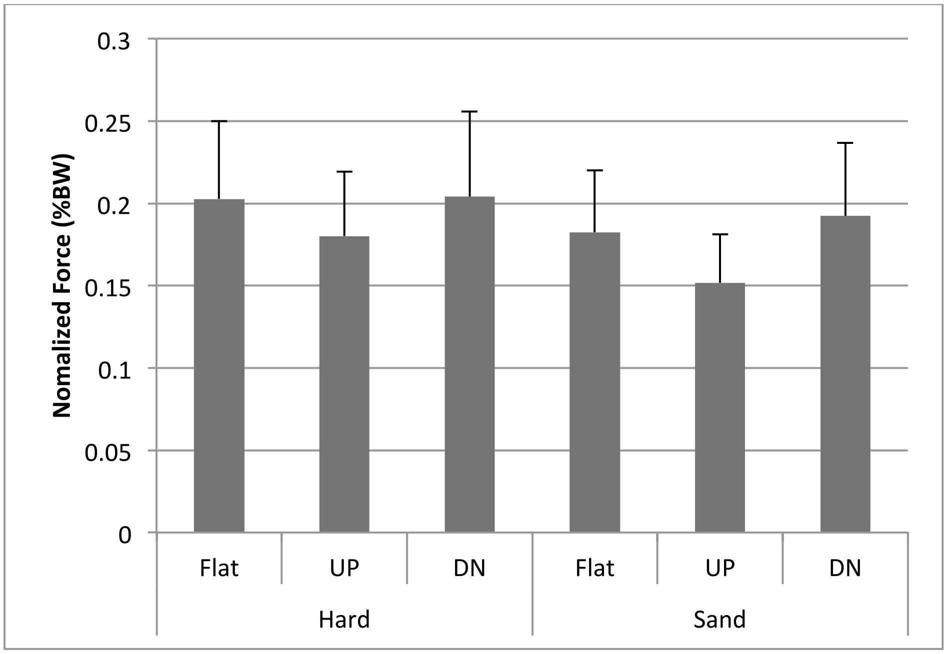

Figure 5-4. Maximum Braking Force by Surface and Slope (*p*=0.001)

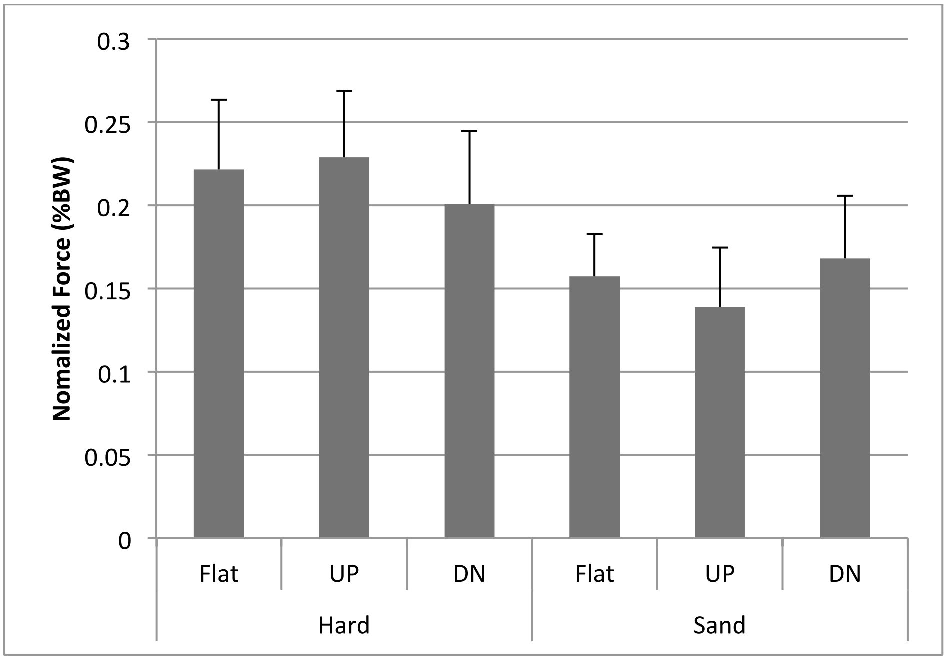

Figure 5-5. Maximum Propulsive Force by Surface and Slope (*p*<0.001)

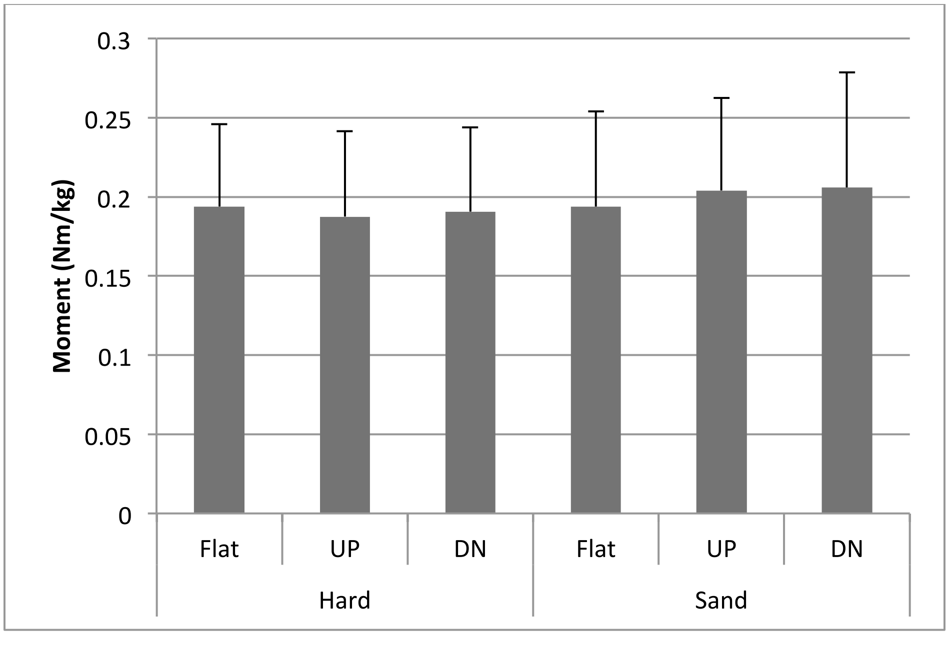

Figure 5-6. Mean Knee Abduction/Adduction Moment by Surface and Slope (*p*=0.015)

Table 5-1. Summary of the main and post-hoc slope effects

	Significant Effect	Post-hoc		
		Flat vs. UP	Flat vs. DN	UP vs. DN
Maximum Vertical Impact Force	Yes	**0.055**	**0.000**	**0.000**
Maximum Vertical Thrust Force	Yes	**0.000**	0.173	**0.001**
Mean M/L GRF force	Yes	**0.003**	0.774	**0.012**
Maximum Braking Force	Yes	**0.000**	0.167	**0.000**
Maximum Propulsive Force	No	0.066	0.063	0.925
Mean Hip A/A Moment	Yes	**0.009**	**0.006**	**0.004**
Mean Knee A/A Moment	No	0.727	0.478	0.796

Note: Numbers in the table represent *p* values.

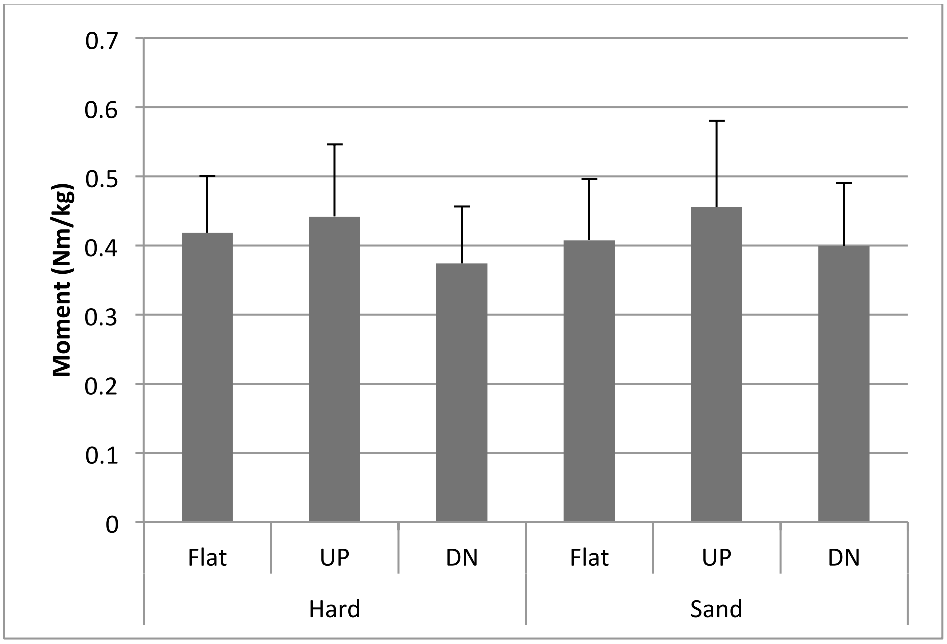

Figure 5-7. Mean Hip Abduction/Adduction Moment by Surface and Slope (*p*=0.027)

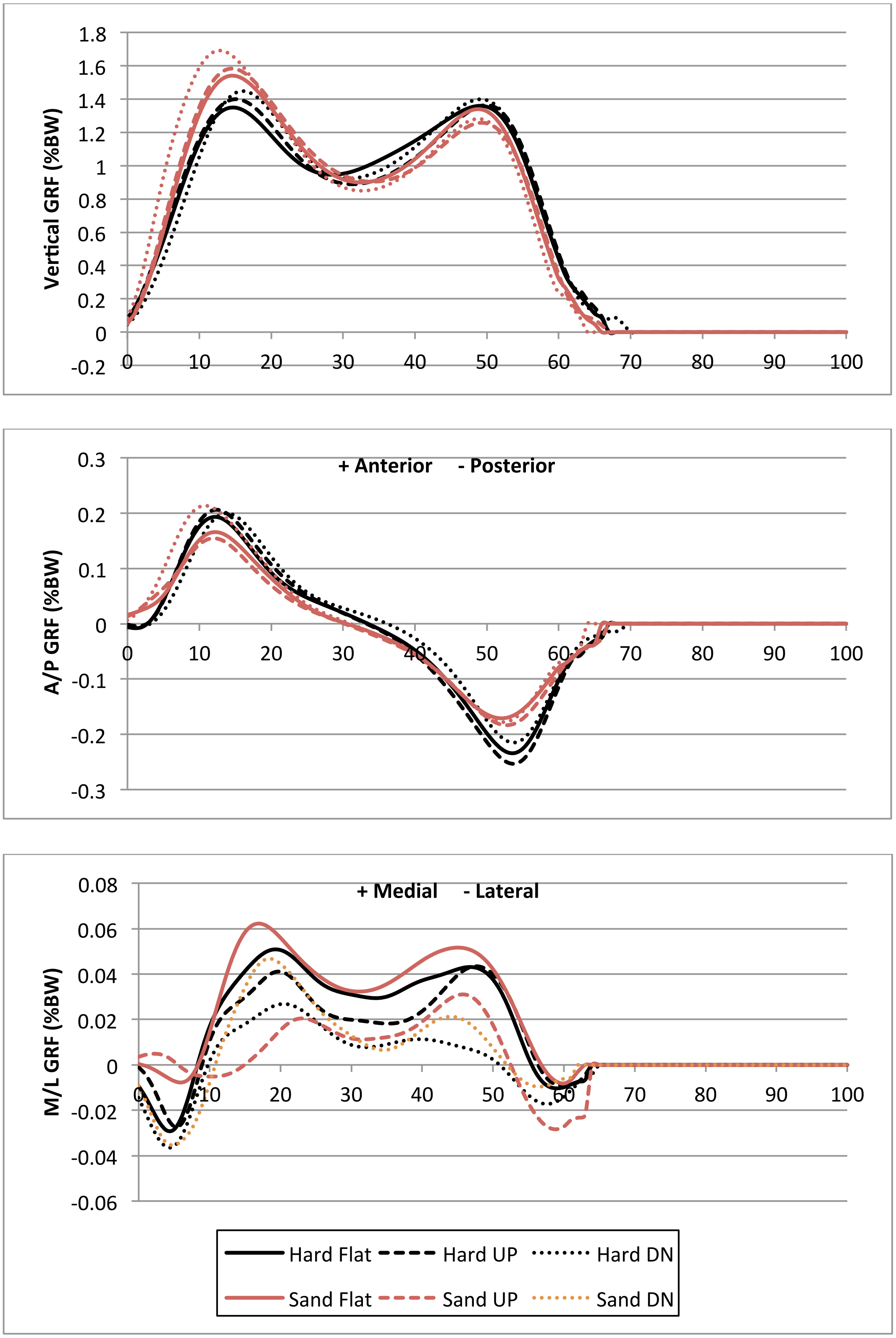

Figure 5-8. Ground Reaction Forces by Surface and Slope

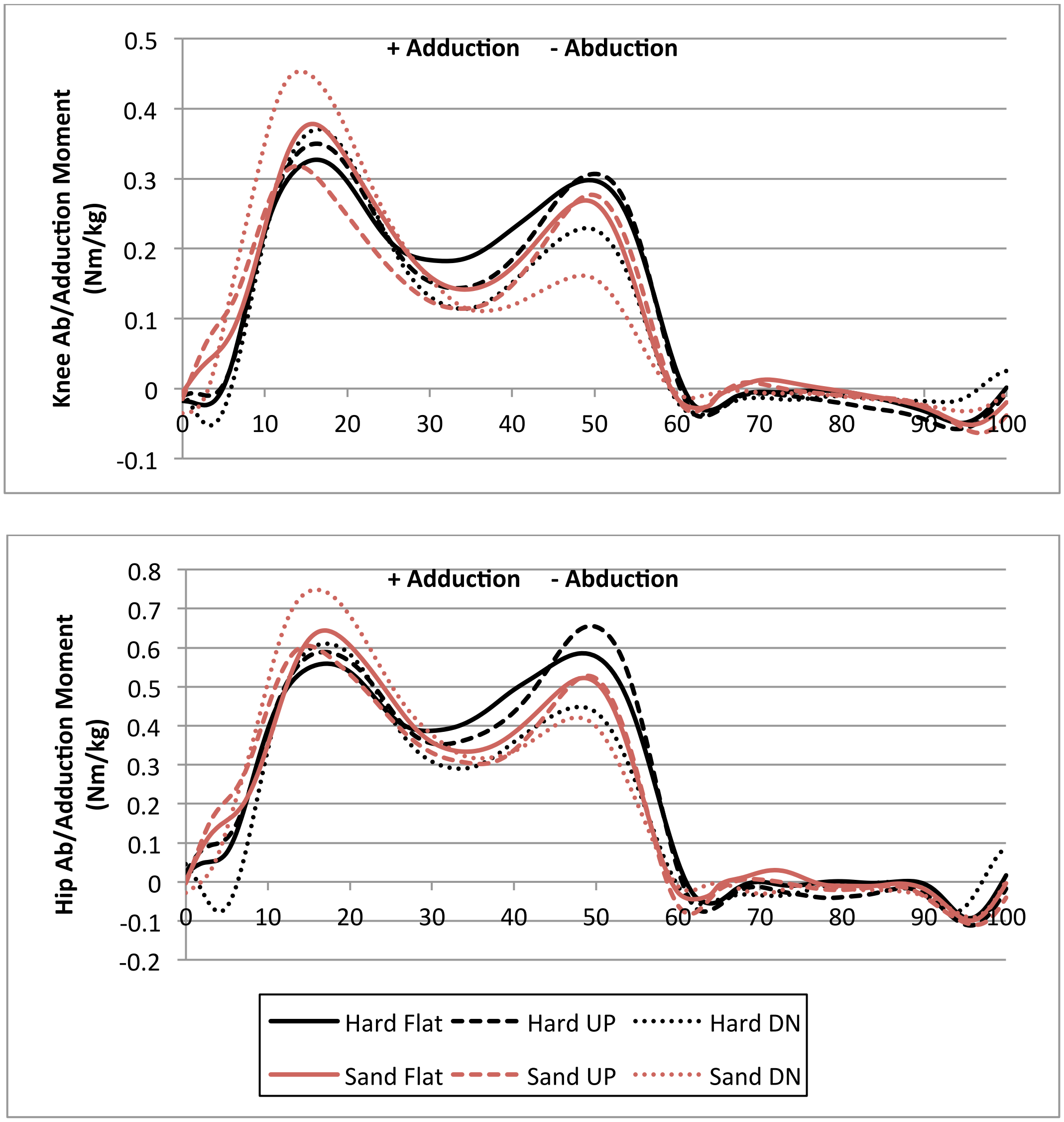

Figure 5-9. Knee and Hip A/A Moments by Surface and Slope

Backpack Effect

There were statistically significant effects among load conditions in all 7 variables. Knee and hip moments were statistically significant when a load was carried. Post-hoc test results are shown in Table 5-2. The results are described in Figure 5-10, Figure 5-11, and Figure 5-12.

Backpack × Surface Effect

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 (p=0.006, p<0.001, p<0.001, p=0.015, p<0.001, and p<0.001). Values are described in Figure 5-13, Figure 5-14, Figure 5-15, Figure 5-16, Figure 5-17, and Figure 5-18. The forces and moments continuous curves by backpack and surface interaction effects are shown in Figure 5-19 and Figure 5-20.

Backpack × Slope Effect

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 (p=0.039, p<0.001, p=0.003, and p=0.001). The results are described in Figure 5-21, Figure 5-22, Figure 5-23, and Figure 5-24.

Table 5-2. Summary of the main and post-hoc backpack effects

	Significant Effect	Post-hoc		
		No vs. MOLLE	No vs. ALICE	MOLLE vs. ALICE
Maximum Vertical Impact Force	Yes	**0.000**	**0.000**	0.293
Maximum Vertical Thrust Force	Yes	**0.000**	**0.000**	0.404
Mean M/L GRF	Yes	**0.000**	**0.000**	0.658
Maximum Braking Force	Yes	**0.000**	**0.000**	**0.007**
Maximum Propulsive Force	Yes	**0.000**	**0.000**	0.688
Mean Hip A/A Moment	Yes	**0.000**	**0.000**	**0.000**
Mean Knee A/A Moment	Yes	**0.000**	**0.000**	0.113

Note: Numbers in the table represent *p* values.

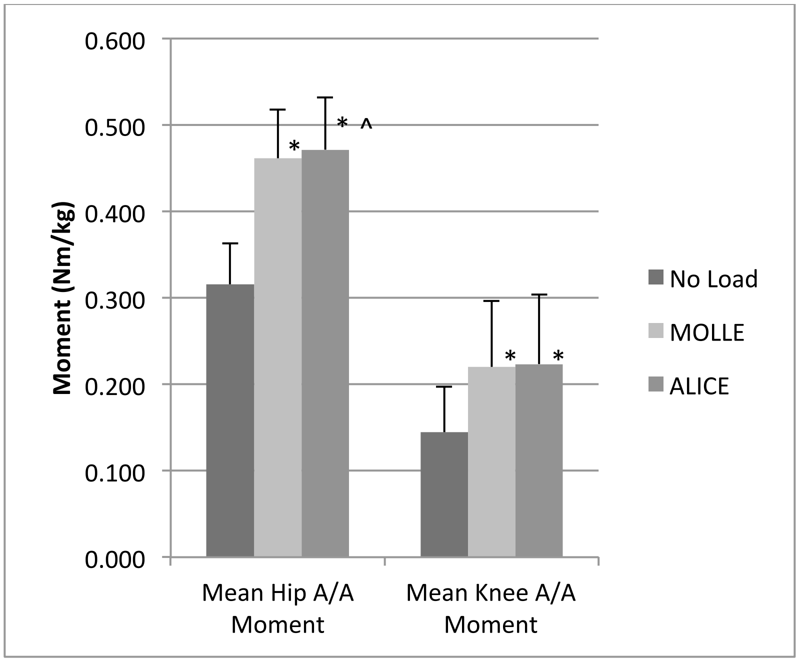

Figure 5-10. Moments by Load Types.
* indicates statistical significance ($p<0.05$) compared to No Load. ^ indicates statistical significance ($p<0.05$) compared to MOLLE.

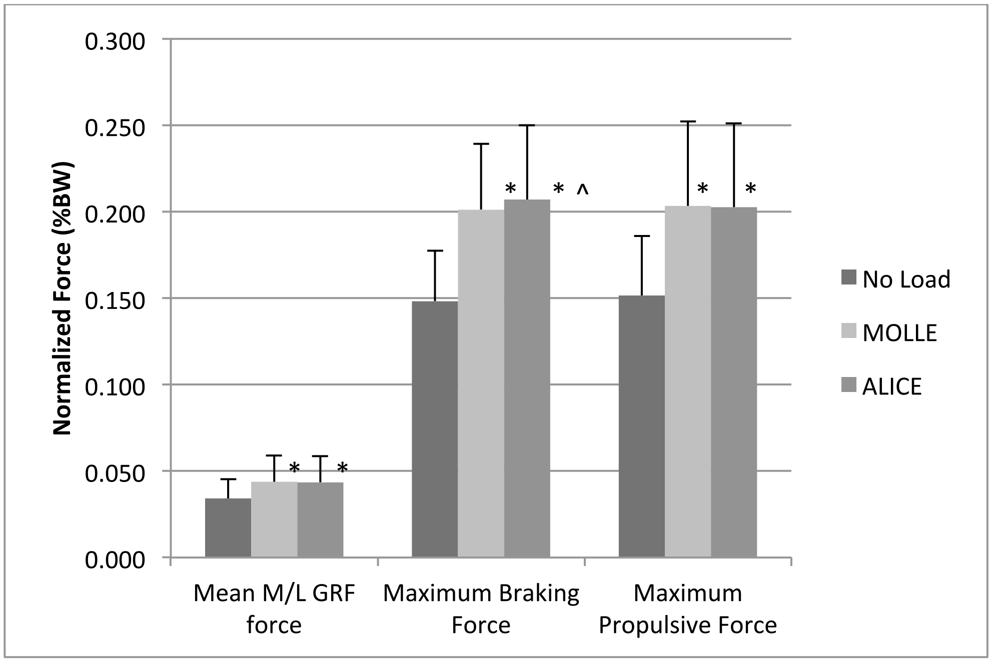

Figure 5-11. GRFs by Load Types
* indicates statistical significance ($p<0.05$) compared to No Load. ^ indicates statistical significance ($p<0.05$) compared to MOLLE.

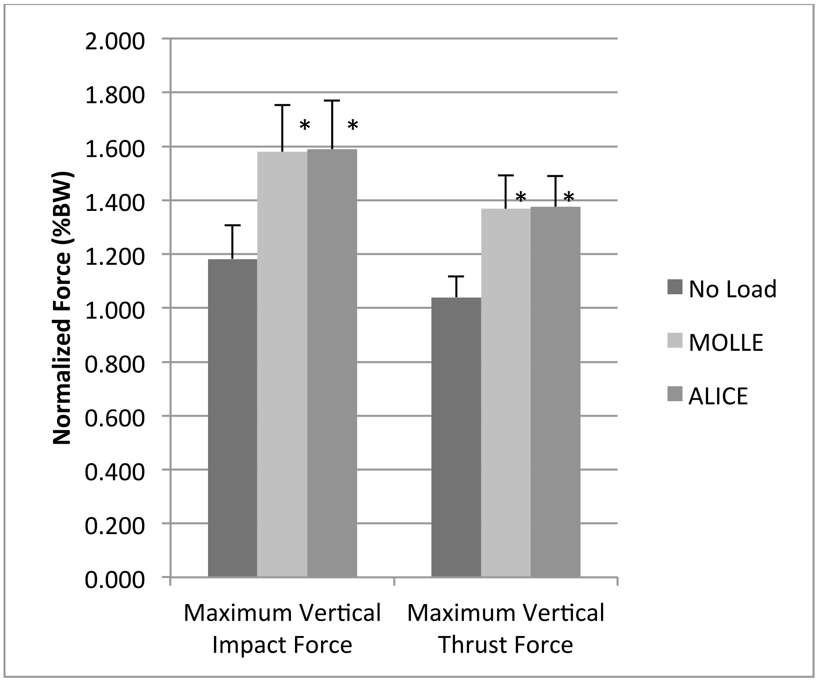

Figure 5-12. GRFs by Load Types
* indicates statistical significance ($p<0.05$) compared to No Load.

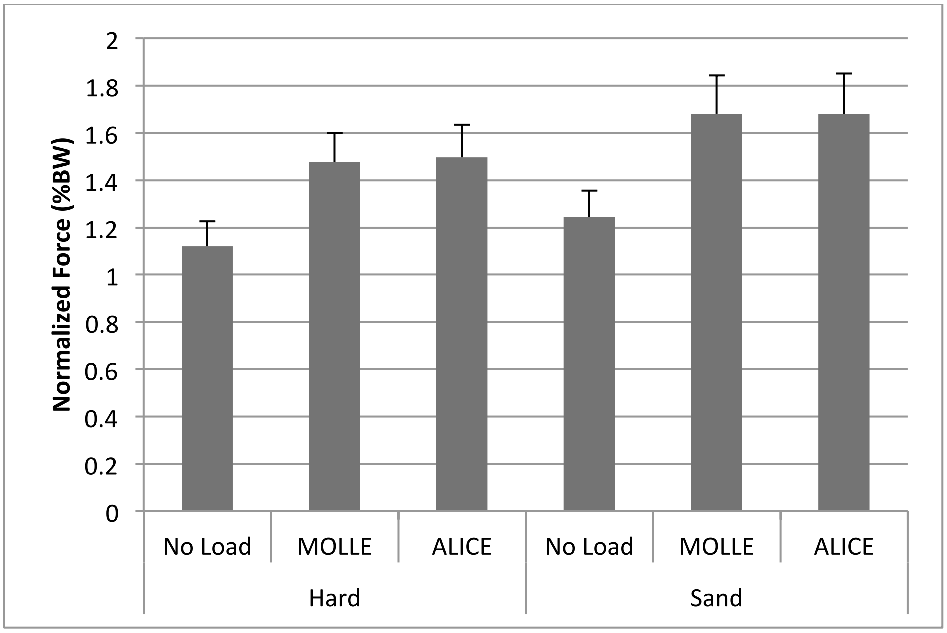

Figure 5-13. Maximum Vertical Impact Force by Backpack and Surface ($p<0.001$)

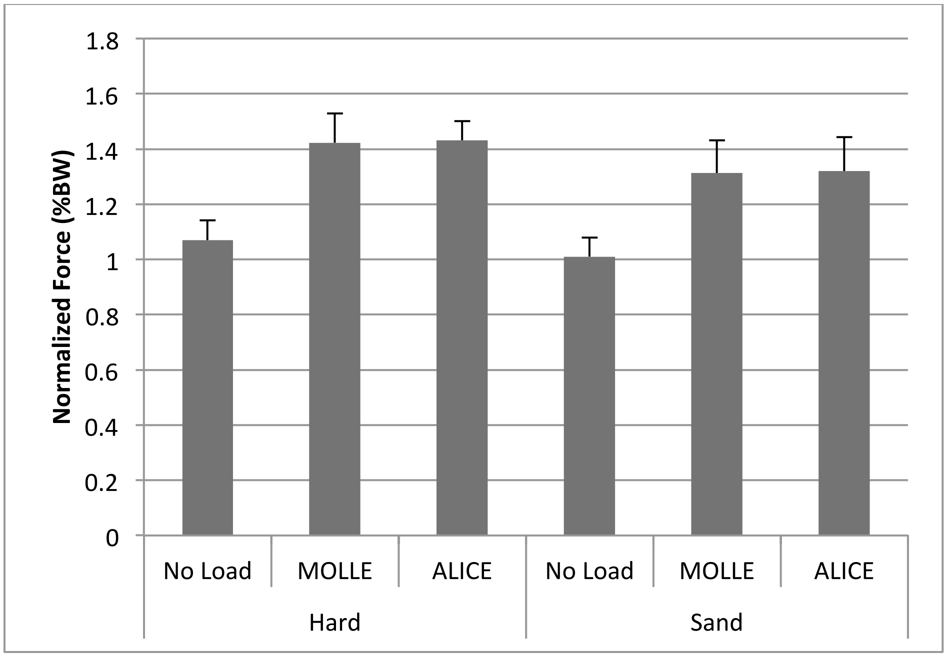

Figure 5-14. Maximum Vertical Thrust Force by Backpack and Surface ($p<0.001$)

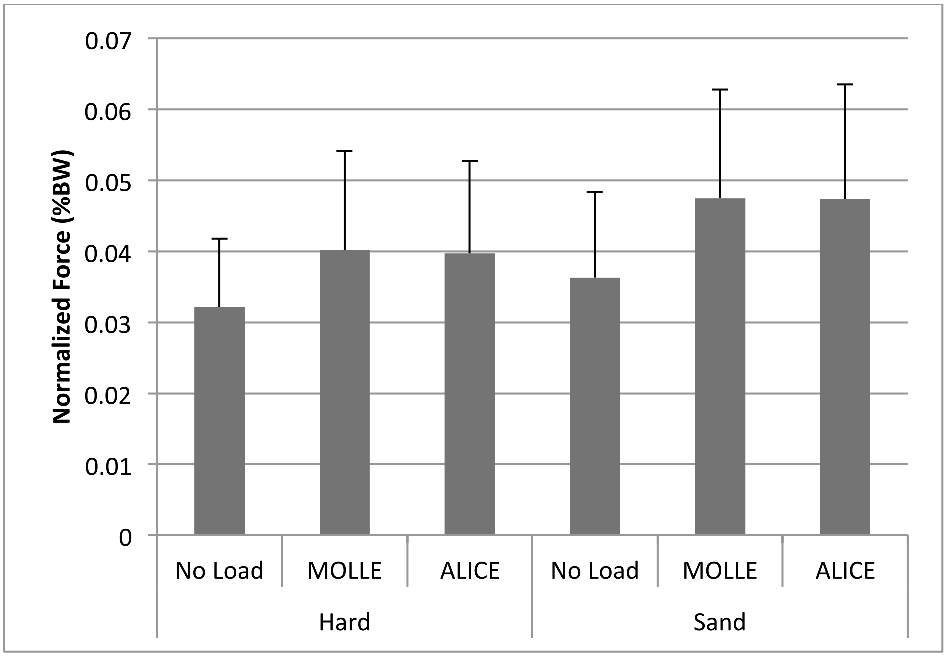

Figure 5-15. Mean M/L GRF by Backpack and Surface ($p=0.006$)

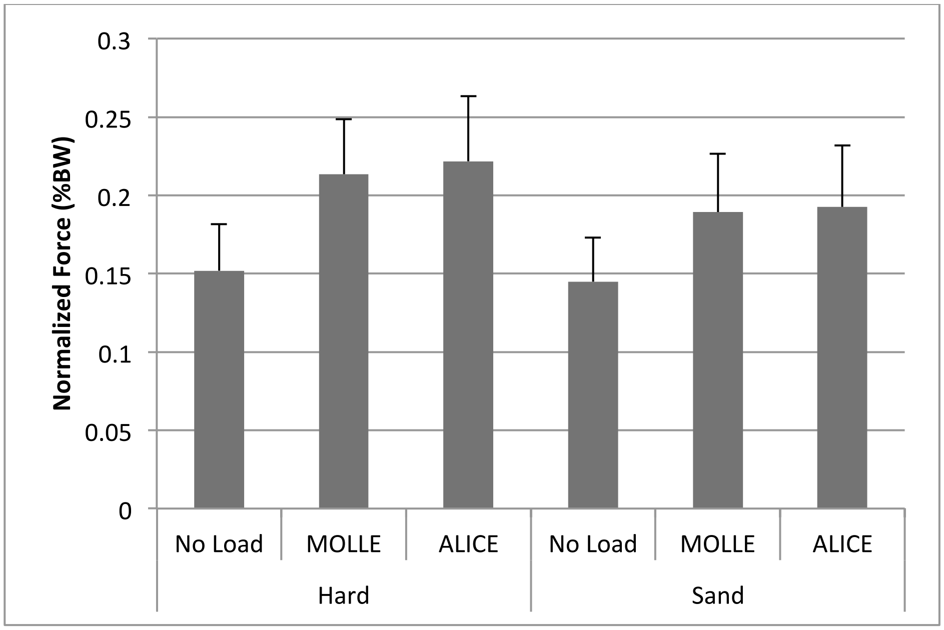

Figure 5-16. Maximum Braking Force by Backpack and Surface (*p*<0.001)

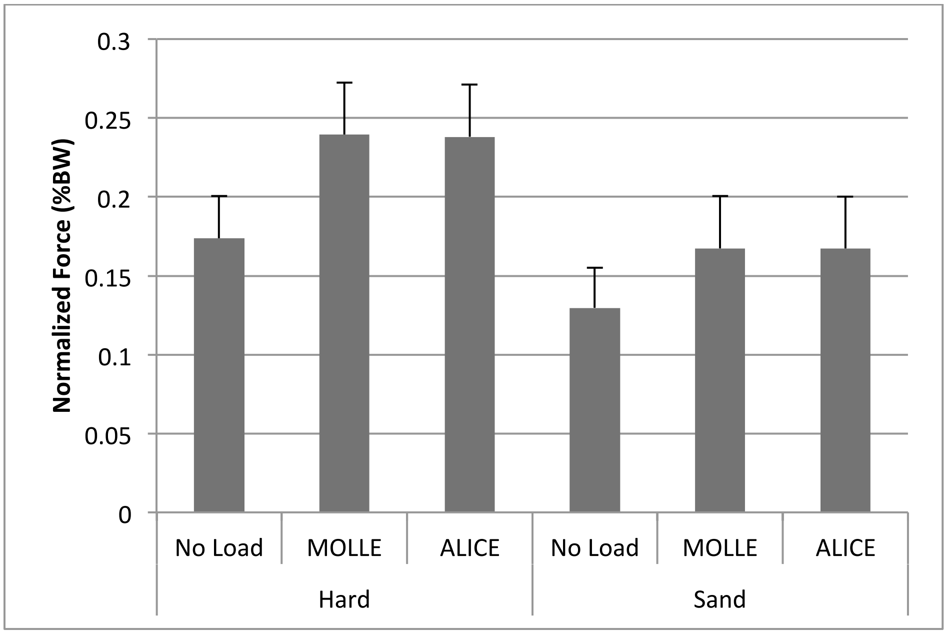

Figure 5-17. Maximum Propulsive Force by Backpack and Surface (*p*<0.001)

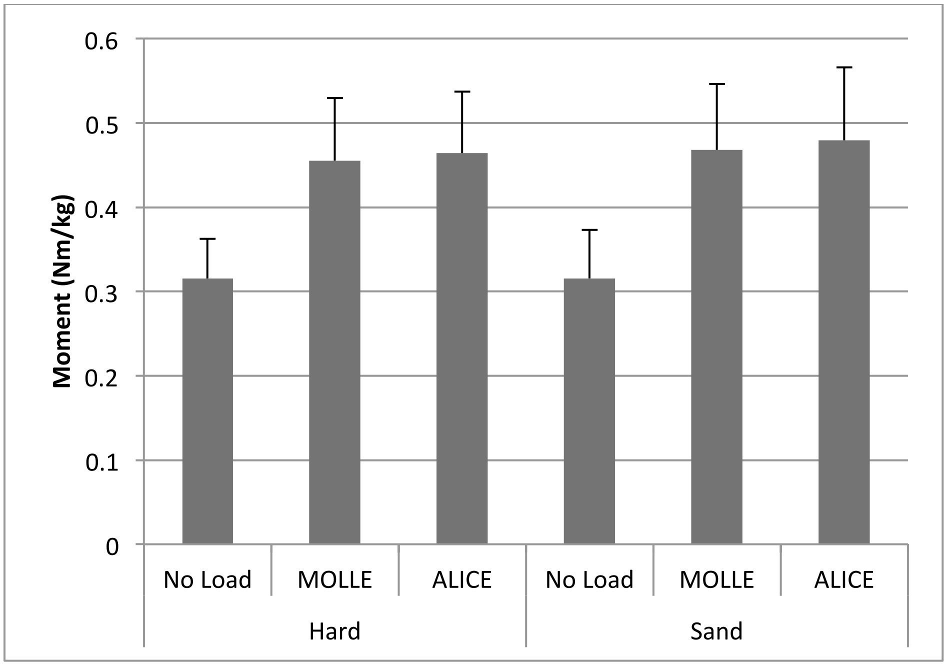

Figure 5-18. Mean Hip A/A Moment by Backpack and Surface (*p*=0.015)

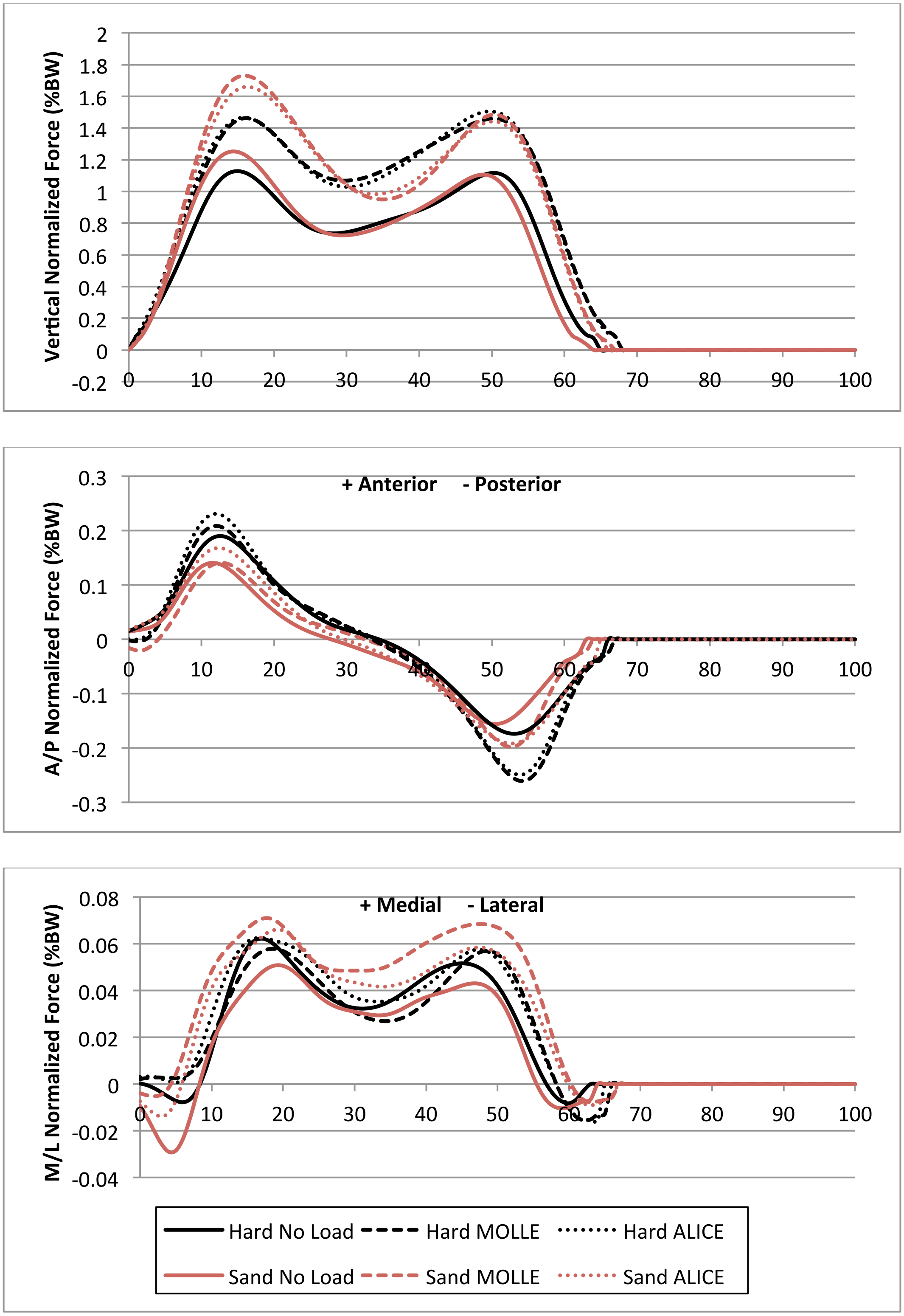

Figure 5-19. Ground Reaction Forces by Backpack and Surface

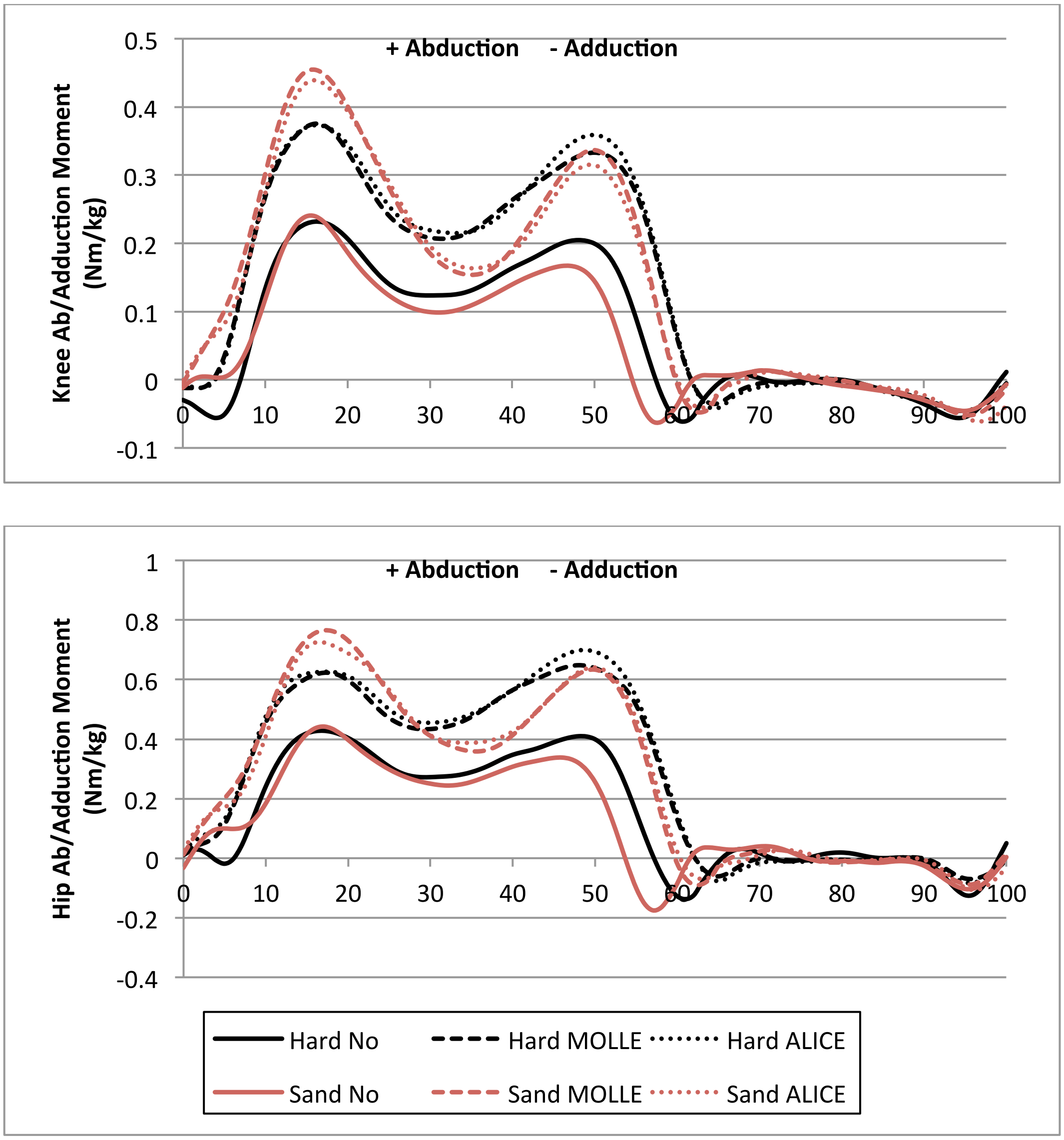

Figure 5-20. Knee and Hip A/A Moments by Backpack and Surface

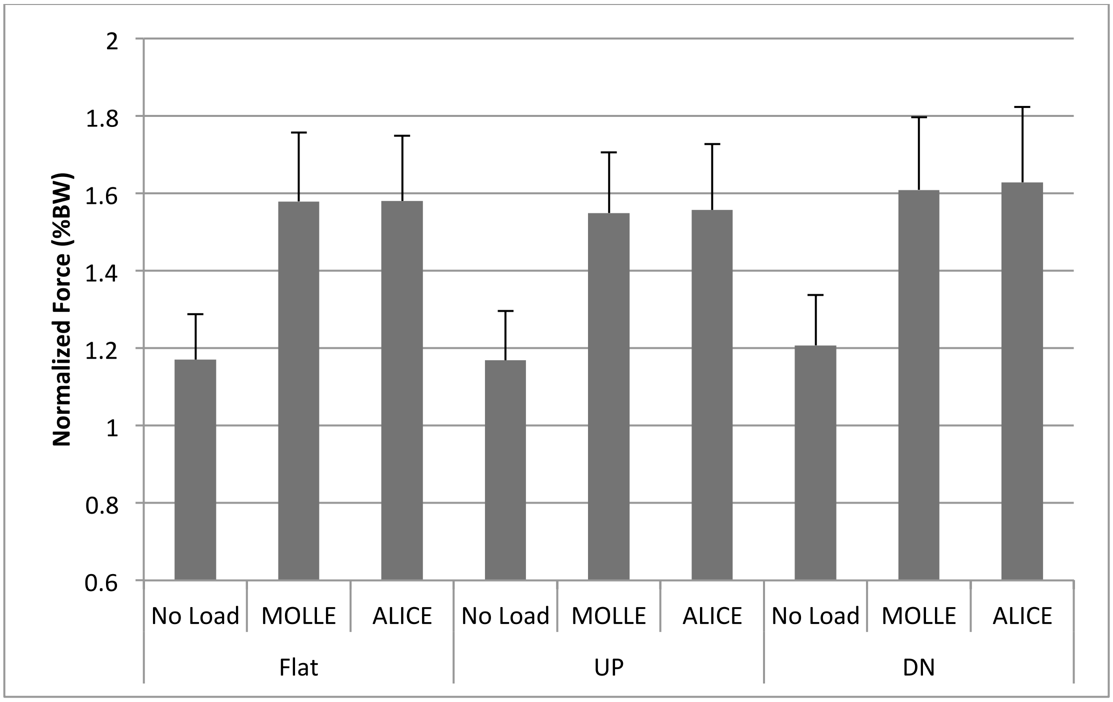

Figure 5-21. Maximum Vertical Impact Force by Backpack and Slope (*p*=0.039)

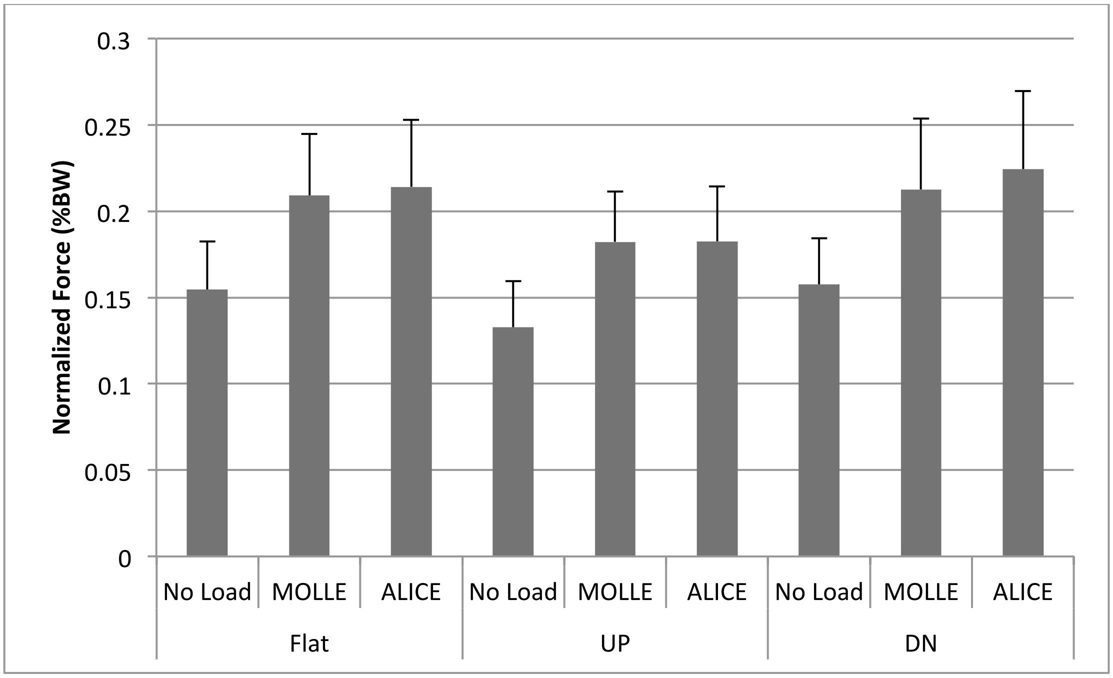

Figure 5-22. Maximum Braking Force by Backpack and Slope (*p*=0.003)

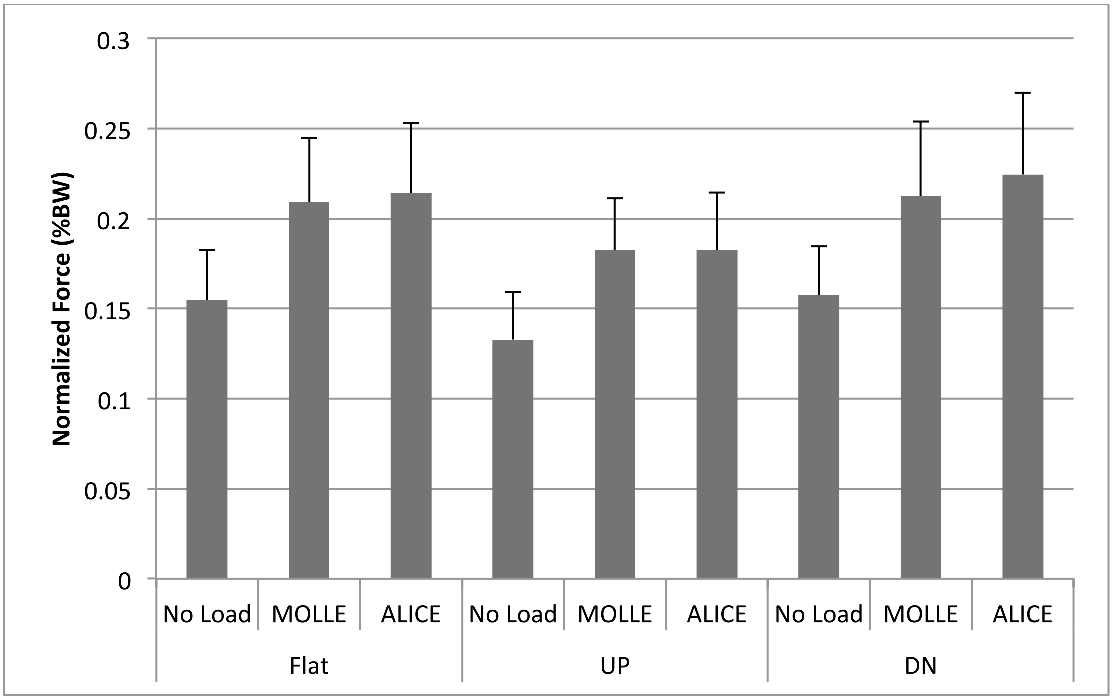

Figure 5-23. Maximum Propulsive Force by Backpack and Slope (*p*=0.001)

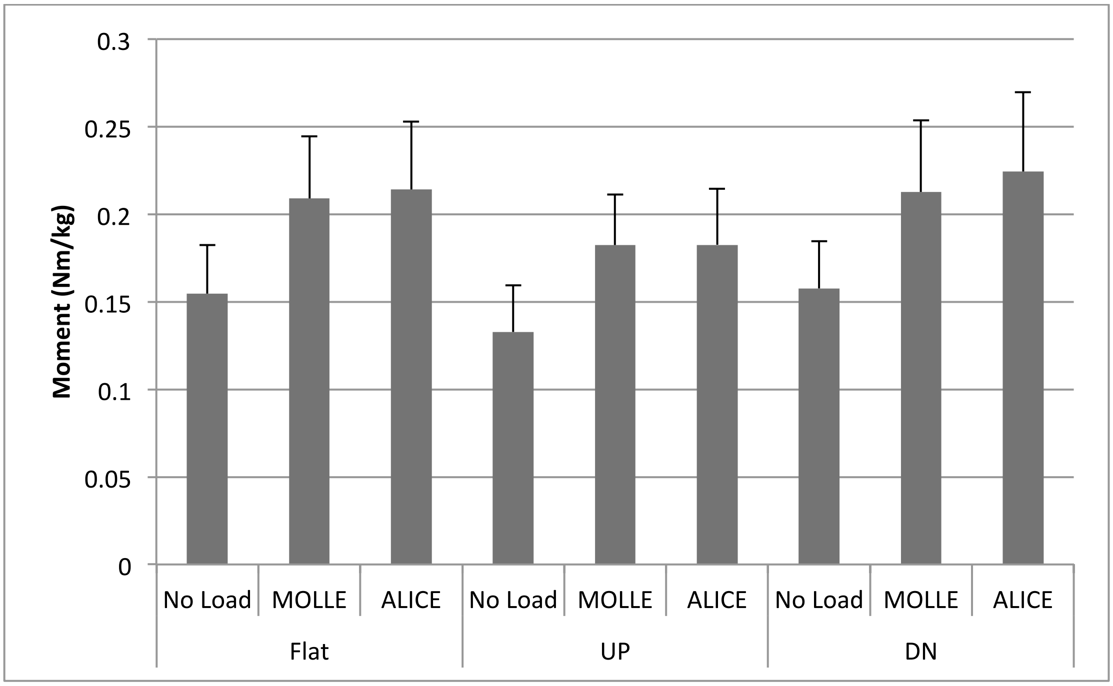

Figure 5-24. Mean Hip A/A Moment by Backpack and Slope (*p*<0.001)

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 investigated in the current study. Hard surfaces had greater maximum thrust forces which indicates a more effective and efficient gait than sand surfaces. However, it had a higher chance of foot strain injury due to the greater vertical thrust force concentrating on the foot metatarsal bone [2]. 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 sway to prevent falling. Previous research confirmed that increased M/L GRFs were observed to avoid fall injuries [28]. The mean M/L GRF increase was observed as load was added [7]. From a backpack/surface interaction effect, the sand surface showed a statistically more significant increase for mean M/L GRF compared to 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 [29]. 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 (Figure 5-21 and Figure 5-22).

Mean knee abduction/adduction (A/A) moment increased significantly on sand surface, compared to hard surface. Added load also contributed to a significant increase in both mean knee A/A moment and mean hip A/A moment. It was found that mean hip A/A moment increased for uphill and decreased for downhill. The mean hip A/A moment was greater for the ALICE than the MOLLE backpack. The trend toward increasing mean hip A/A moment for ALICE was also investigated from backpack/surface interaction and backpack/slope interaction effects. A high risk of injury was confirmed from other researches with increased hip A/A moment [28, 30]. Knee abduction moment during walking is increased as load is added and may heighten the risk of joint injury and degeneration [31]. Another study showed that there was a statistically significant relationship between knee adduction moments and knee osteoarthritis [32].

Conclusion

Overall, walking on a sand surface or wearing a heavy military backpack had greater injury risk due to: 1) increased vertical impact force and decreased vertical thrust force. They increase greater lower limb overuse injury and reduce comfort 2) increased M/L GRF. For a healthy young individual, the surface condition may not increase the injury potential; however, high injury risk is expected with an added load 3) increased knee abduction/adduction and hip abduction/adduction moment. They 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 contributes to common injuries, including stress fractures, knee pain, foot blisters, and metarsalgia. Sand surfaces may increase overuse injuries due to higher impact forces. ALICE (0.472 Nm/kg) backpack is expected to have increased lower limb injury potential because of increased hip A/A moment compared to MOLLE (0.462 Nm/kg) if the soldier exposed a prolonged amount of time with repetitive walking gait cycles.

It is obvious that reducing the total load seems to be the most simple and quick solution. This could be accomplished by using lightweight equipment and by packing only necessary items based on operations. Therefore, different packing items and strategy is necessary depending on an individual operation instead of applying the general packing strategy to all military operations. A light backpack will eventually decrease the potential lower limb injuries and increase operation performance.

Footwear with extra shock observant material installed can have a substantial influence on the hip, knee, and ankle moments and forces with an appropriate application. Individual walking pattern and style need to be investigated using lower limb gait experiments. 3D motion analysis can be utilized to determine body postures and gait patterns to further prevent injuries as the moments and forces are closely related to the shape of legs or patterns of walking.

References

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CHAPTER 6

CONCLUSION

The goal of this study was to provide understanding about lower limb biomechanics while walking on sand and transverse slope surfaces and carrying military backpacks. This study has a unique environmental setup comprised of adjustable walkways containing has sand with embedded force plates. This setup provides a more ecologically valid research environment using instrumented irregular surfaces. Chapter 1 introduced a brief background of this study and the previous literature regarding military injuries, surface conditions and loads. Chapter 2 explained the methods and other techniques used in this study. Chapters 3, 4, and 5 included spatial-temporal effects (Chapter 3), kinematic effects (Chapter 4), and kinetic effects (Chapter 5).

Synopsis of Chapter 3

1) Cadence significantly decreased on the sand surface compared to the hard surface. The current study detected a significant speed decrease on the slanted surface as well. Cadence has a trend toward decreasing in the following order: hard flat, hard slanted, sand flat, and sand slanted.
2) Double support time increased as the load increased and as the slope increased. However, double support time decreased on the sand surface as

compared to the hard surface. Double support time decreased as walking speed increased. Double support time was the smallest on the sand-slanted surface among the surface and slope interactions.

3) Added load resulted in a significant decrease in stride length. Stride length decreased on the sand surface, compared to the hard surface.
4) Stride width decreased on the slant surface compared to the flat surface. Stride width was not significantly different as the load was added. However, the MOLLE had a larger stride width than the ALICE (*p*=0.008).

Synopsis of Chapter 4

1) The RoM of the ankle dorsi/plantarflexion, knee flex/extension, and hip flex/extension angles increased on the sand surface compared to the hard surface. The RoM of each joint angle in the sagittal plane increased on an uphill, compared to a flat surface.
2) With the added load, the knee flexion/extension RoM angle was decreased for the hard surface. However, knee flexion/extension RoM angle was increased with added load for the sand surface. An increased knee flexion angle was observed at heel strike for both hard and sand surfaces as the load increased.
3) Increased hip flexion/extension RoM for the uphill and for the sand surface was investigated. Increased ankle dorsiflexion was also investigated throughout the stance phase to decrease the uphill leg length. The sand surface required increased ankle dorsiflexion in comparison to a hard surface.

4) In the coronal plane, ankle inversion/eversion RoM angles were greater on the sand uphill surface. With added load, knee medial/lateral and rotational movement decreased.
5) On the sand surface, the knee flexion/extension RoM increased when the backpack was carried. The ankle dorsi/plantarflexion on the sand surfaces increased when a load was carried.
6) There were greater hip abduction/adduction RoM angle in the MOLLE than in the ALICE. It may be said that soldiers carrying the MOLLE backpack may pose a higher risk for hip overuse injuries than those carrying the ALICE backpack.

Synopsis of Chapter 5

1) The maximum vertical impact force was greater on the sand surface. The maximum vertical impact force increased as the load was added. The maximum vertical thrust force was greater on the hard surface. The maximum vertical thrust forces decreased on uphill.
2) The mean M/L GRF was greater on the sand surface, compared to the hard surface. A significant mean M/L GRF increase was observed on the sand downhill condition. A mean M/L GRF increase was observed as the load was added.
3) Both the maximum braking and the maximum propulsive forces increased significantly on the hard surface. Increased maximum braking and maximum propulsive forces were observed with the added load. The maximum braking

force and the maximum propulsive force for the ALICE were greater than those for the MOLLE in regards to backpack/surface interaction effects and backpack/slope interaction effect.

4) The mean knee abduction/adduction (A/A) moment increased significantly on the sand surface. The mean knee A/A moment and mean hip A/A moment increased with the added load. The mean hip A/A moment increased for uphill and for the ALICE.

In summary, walking on the sand surface resulted in a significant decrease in cadence and double support time. In kinematic parameters, the ankle dorsi/plantarflexion and inversion/eversion, knee flexion/extension, hip flexion/extension RoM angle all increased on the sand surface. In kinetic parameters, the mean M/L GRF, the maximum vertical impact force, and the mean knee abduction/adduction moment increased on the sand surface. As a result, walking on sand surface increased in instability, ankle ligament injury, and metatarsalgia risk on the foot, and a greater chance of lower limb overuse injury.

The MOLLE backpack had a larger stride width, increased hip abduction/adduction RoM angle than the ALICE backpack, which was possibly due to the increased medial/lateral RoM. As a result, increased risk for hip injury are expected with the MOLLE backpack. From the result of the kinematic effects, using the MOLLE backpack may increase the soldier’s exposure to a high risk of hip overuse injuries. From the kinetic effects, the ALICE backpack may increase lower limb injury potential because of the increased hip moment in the frontal plane and the higher braking/propulsive forces.

Therefore, the marching strategy on sand surface while carrying a military backpack for the soldiers should be carefully considered to further reduce lower extremity musculoskeletal injuries. Some of the considerations to reduce lower limb injuries are overall backpack weight, optimizing training based on individual's physical capability, analyzing individual's gait to correct abnormal gait patterns, using different military boots, changing packing strategy based on the operation by removing unnecessary items, and minimizing exposures to uneven surface conditions.

Future Work

These results provide a useful understanding of human gait on a sand surface while wearing MOLLE and ALICE backpacks. While performing the research and analyzing/interpreting the data, some of the following limitations were addressed:

1) To understand each backpack fully, the waist belt should be applied as it was intended. The current study did not control the waist belt to minimize the waist belt effect.
2) Gait studies on the sand surface by changing backpack weights based on operation types would be helpful to understand the effect of different loads on different military operations. The possible independent variables could be backpack weights and types of other accessories, such as a helmet, a weapon, body armour, and a respirator.
3) Different boots would affect the kinetic parameters based on the current discussion so studies of gait while wearing different military boots could increase the knowledge to select better boots by operation types.

4) Studies on how different military training protocols affect gait parameters could help optimize the military training based on the expected terrain and operation types.