Lifting Performed on Laterally Slanted Ground Surfaces

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Many outdoor work environments (e.g. agriculture and construction) require manual material handling activities on variable grade ground surfaces. Quantifying biomechanical responses for lifting under these conditions may provide insight into the etiology of lifting-related injuries. The aim of the current study was to quantify the effect of laterally slanted ground surfaces on biomechanical responses. Ten subjects performed lifting exertions (using a 40% of max load) while standing on a platform that was laterally tilted at 0, 10, 20 and 30 degrees from horizontal. During the lifting tasks the whole body kinematics were collected, which were later used in a dynamic biomechanical model to calculate the time-dependent moment about L5/S1 and the time-dependent lateral forces acting on the body segments. The results showed a consistent reduction in the peak dynamic L5/S1 moment (decreased by 9%) and an increase in the lateral forces (increased by 111%) with increasing slant angle.

INTRODUCTION

Manual material handling tasks on uneven terrain are prevalent in many outdoor industries (e.g. agriculture and construction) and present an interesting challenge for ergonomists. It is believed such external environmental characteristics may influence the technique as the lifter seeks to maintain stability and perform the lift safely. Understanding the nature and developing a quantitative description of these changes may provide the basis for appropriate ergonomic interventions and is the focus of the current work.

Previous research has shown that a sloped (forward/backward in the sagittal plane) ground surface can result in larger horizontal reaction force on feet (Zhao et al, 1987), reduced body stability (Simeonov et al, 2003) and changes in joint range of motion (Shin and Mirka, 2004). Zhao et al. simulated fruit growing fieldwork to assess the influence of sloped (sagittally) ground surface angle on slip risk (Zhao et al., 1987). The results showed horizontal reaction force, indicating slip potential, was significantly higher on sloped surface and the positional variation of the body center was less with back lifting. They also noted that the motion of the center of gravity as measured by the force platform was reduced when the lifters used the squat lifting technique vs. the stoop lifting technique. Simeonov et al. investigated the standing balance in construction workers during the roof work (with declined slope in sagittal plane), where slope angle showed significant effects on the postural sway in anterior-posterior direction and the velocity of sway (Simeonov et al., 2003). These authors make the recommendation for temporary structures that provide a portable horizontal surface to reduce the effort for balance control. Finally, Shin and Mirka investigated the effects of sloped (forward/backward) ground surface on lifting performance (Shin and Mirka, 2004). They assessed the reactive moment at L5/S1 joint and its components during sagittally symmetric lifting (back, leg, and freestyle lifting) on two upward slopes (10° and 20° in sagittal plane), two downward slopes (10° and 20° in sagittal plane), and flat ground. The peak reactive L5/S1 moment was significantly affected by surface angle in leg and freestyle lifting and showed increasing trend as surface angle increased from 0° to upward 20°. The postural adaptation of the body to keep the whole body balanced on sloped surface was found as the main driving reason that caused the change of L5/S1 moment.

In comparison to a sagittally sloped surface, a laterally slanted surface may cause different biomechanical responses during a lifting task. Such lifting involves non-symmetric postures such as different ankle angle and knee flexion angles for the left and right side, and also lateral trunk bending/rotation. Previous work has shown lateral bending velocities to be a significant risk factor for LBDs (Marras et al., 1993).

The aim of this study was to quantify the effects of a laterally slanted ground surface on the lifting kinematics. It was hypothesized that the lifting kinematics would be altered to reduce the speed of the lifting motion and thereby reduce L5/S1 moment. It was also hypothesized that the changes in the lifting kinematics would be insufficient to overcome the lateral instability generated with the increasing lateral ground slope and therefore the peak net lateral forces generated by considering the lateral acceleration of the body segments would increase as a function of increasing ground slope.

METHOD

Subjects

Ten subjects (seven males and three females), all free from chronic and current back injury, were recruited from the University community. The subject group had a mean (and standard deviation) age of 28 years (3.6 years), stature 174 cm (5.9 cm), and body mass 71.3 kg (12.5 kg). All subjects gave written consent after being informed of the nature and potential risks of the experiment.

Apparatus

Experimental task. A platform was built that provided a ground surface that could be adjusted to four levels of lateral slant (0°, 10°, 20°, and 30°). The platform surface was plywood and was covered with a cloth matting material that provided a high coefficient of friction for the lifter. Subjects lifted a .3m x.3m x.3m wooden box with cutout handles that held a set of steel plate weights that corresponded to 40% of each subject's trunk extension capacity as established during a maximum voluntary trunk extension exertion.

Data collection. Six motion sensors from a magnetic field-based Flock of Birds motion tracking system (Ascension Technology Corporation, Burlington, VT) were used to collect the lifting kinematics data. This motion sensor system provided time-dependent information about x, y, z coordinates and roll, pitch and yaw of each of the six sensors. The motion data were collected at 60 Hz.

Experimental Design

The independent variable in this study was the lateral ground slope angle (Angle) with four levels: 0°, 10°, 20°, and 30° tilted towards left.

The dependent variables were the peak L5/S1 moments for each lifting motion and peak net lateral forces (both rightward and leftward). All of these variables were calculated using a dynamic biomechanical model (introduced later) that utilized the data from the motion analysis system.

Experimental Procedures

All subjects began with a stretching and warm up period. Six motion sensors were then placed on the lateral projection of the center of mass of both upper legs, lateral projection of the center of mass of both arms, posterior side upper back at T9, and on the lateral side of the center of the box. During the experimental trials, subjects were asked to always keep the left knee straight and to bend the right knee as needed to conform to the platform tilt. Subjects stood on a flat surface and performed two or three freestyle lifts while movements were collected and analyzed briefly to verify sensor assignment and orientations. After one-minute break, the lifting trials began. Each trial was performed under one level of Angle and lasted for 40 seconds, during which subjects performed five repetitive freestyle lifts (eight seconds each). In each lift, subjects started from neutral, upright standing position, bent down to grab the box located on the platform and ended with the subjects returning to their original standing position with the box in their hands and arms straight. When the subjects' body was stable, the box was taken and returned to its original location by the experimenter. The starting location of the load relative to the platform was fixed throughout the lifting trials. Each trial began with the examiner's notice ('Go') and subsequent lifts were initiated by the experimenter's verbal signals ('Lift'). There were a total of eight lifting bouts (four surface angles and two repetitions per each angle), and the order of trials was randomized. There was a fifteen-second rest break between consecutive trials, during which the platform slant angle was adjusted to the next setting. Special attention was paid to ensure that the projection of subject's both ankles cast on the platform remained fixed throughout the experiment, and that the center of the load was on subject's sagittal plane. Therefore, the distance between the initial center of the load and subject was constant throughout the data collection.

Data Processing

The kinematic data captured during the lifting trials were processed to obtain the necessary time-dependent inputs for the biomechanical models. These raw data were processed using the Motion Monitor™ Ver. 4.0 (Innovative Sports Training, Inc, Chicago, IL) software and the same parameters and methods were used as in Shin and Mirka (2004) for filtering and acceleration derivation.

Biomechanical Models

Two biomechanical models were established to calculate the time-dependent L5/S1 moment and net lateral forces.

The same biomechanical model utilized in Shin and Mirka (2004) was used to calculate the L5/S1 moment. This biomechanical model included the gravitational factors, linear (horizontal and vertical) acceleration factors, and moment-of-inertia (angular acceleration) factors for each body segment. In this model, we assumed that body segments were connected by frictionless hinge joints, and joint moments, if any, were solely generated by muscles around the joints. It was also assumed that the upper extremity (arms and hands) acted as a single segment (i.e., no elbow flexion was involved throughout lifts as was observed during pilot study), and the moment between hands and the handles of the load was negligible. Therefore, the L5/S1 moment consisted of the following components: (1) moment at shoulder joint; (2) moment generated by static vertical reaction force acting on shoulder joint; (3) moment generated by dynamic vertical reaction force acting on shoulder joint; (4) moment generated by horizontal dynamic reaction force acting on shoulder joint; (5) moment generated by gravitational force acting on trunk; (6) moment generated by dynamic vertical force acting on trunk; (7) moment generated by horizontal dynamic force acting on trunk; (8) moment of inertia of torso about L5/S1 joint x angular acceleration of the trunk (Figure 1). Each of these components was quantified at each point in time, and when the peak L5/S1 moment was identified, the value of each component at that instant in time were saved to allow for a more detailed component analysis.

A second dynamic biomechanical model was necessary to estimate the time dependent net lateral force. In this model the mass of each body segment was estimated using the anthropometric estimates of McConville et al. (1980) and Pheasant (1996) and the lateral accelerations of the load and the body segments (torso, bilateral arms, bilateral thighs) as measured by the motion tracking system. At each instant in time the sum of these forces (m x a) was calculated. As in the calculation of the peak L5/S1 moment, each of the components that made up the net lateral force were quantified at each point in time, and when the peak net lateral force was identified, the value of each component at that instant in time

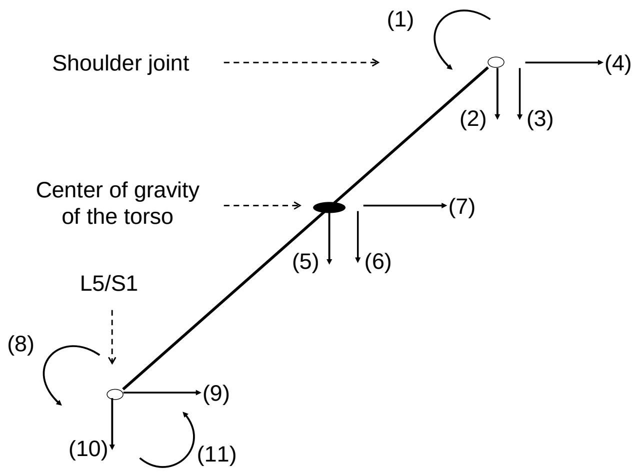

Figure 1. Free body diagram of the torso (head-neck-trunk): (1) moment at shoulder joint; (2) static vertical reaction force acting on shoulder joint; (3) dynamic vertical reaction force acting on shoulder joint; (4) horizontal dynamic reaction force acting on shoulder joint; (5) gravitational force acting on torso; (6) dynamic vertical force acting on trunk; (7) horizontal dynamic force acting on trunk; (8) moment of inertia of torso about L5/S1 joint x angular acceleration of the trunk; (9) horizontal reaction force at L5/S1; (10) vertical reaction force at L5/S1; (11) L5/S1 moment.

were identified to allow for a more detailed component analysis of which factors were responsible for the trends in the net lateral force.

The end result of this biomechanical modeling exercise was a time-dependent description (Figure 2) of the L5/S1 moment (and its components) and net lateral force (and its components) and the dependent variables were derived from each lift using these profiles in the following way. Each set of motion sensor data, corresponding to one trial, consisted of data from five identical lifts. The data set was partitioned into five sections each with a width of eight seconds (see Figure 2). For each section (lift), the peak L5/S1 moment and the peak of the net lateral force (both rightward and leftward) were identified.

Data Analysis

ANOVA was applied to examine the effect of slant angle on the dependent variables. A p-value of less than 0.05 was used as the criteria for significant effect. A Tukey-Kramer post hoc analysis was employed when any significant difference was found by the ANOVA.

RESULTS

The results of the analysis of the peak L5/S1 moment showed a significant Angle effect with a consistent reduction (decrease of 9%: horizontal to 30° condition) in this moment with increasing lateral slant angle (Figure 3). In the analysis of

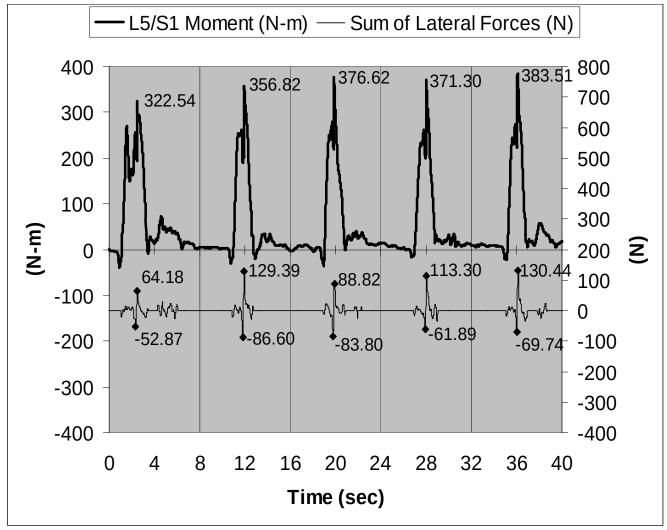

Figure 2. Illustration of the time-dependent L5/S1 moment and net lateral force. Peaks of each used in the data analysis are also identified.

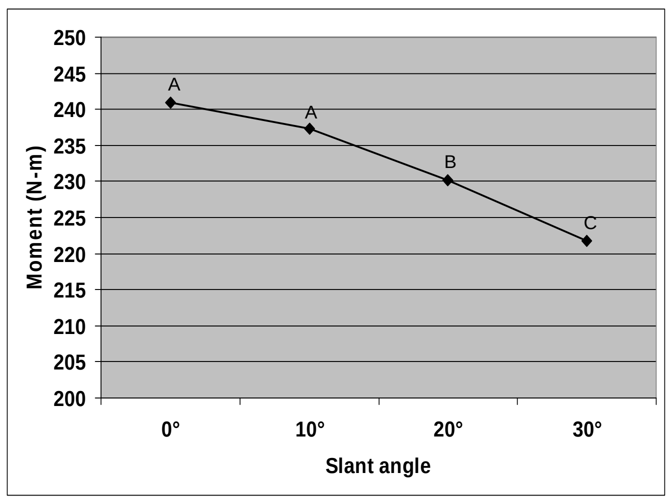

Figure 3. Peak L5/S1 moments as a function of lateral slant angle.

the components that comprised this peak moment value, we found that the component describing the moment created by the dynamic inertial forces (vertical and horizontal forces on the torso and the rotational inertia of the torso) were those most affected by the increase in the level of Angle (Figure 4) indicating that it appears that the subjects were slowing down the lifting motion with greater lateral slant angle, presumably to be more cautious and maintain stability.

The analysis of the net lateral force results showed that increasing level of Angle generated a 111% increase in the peak lateral forces (Figure 5). Component analysis of this effect showed that both the side-to-side movement of the load and the torso contributed to this response. It is interesting to note that the leftwards forces (down the slant) were shown to be consistently larger than the rightwards forces across all angles ($p<0.05$).

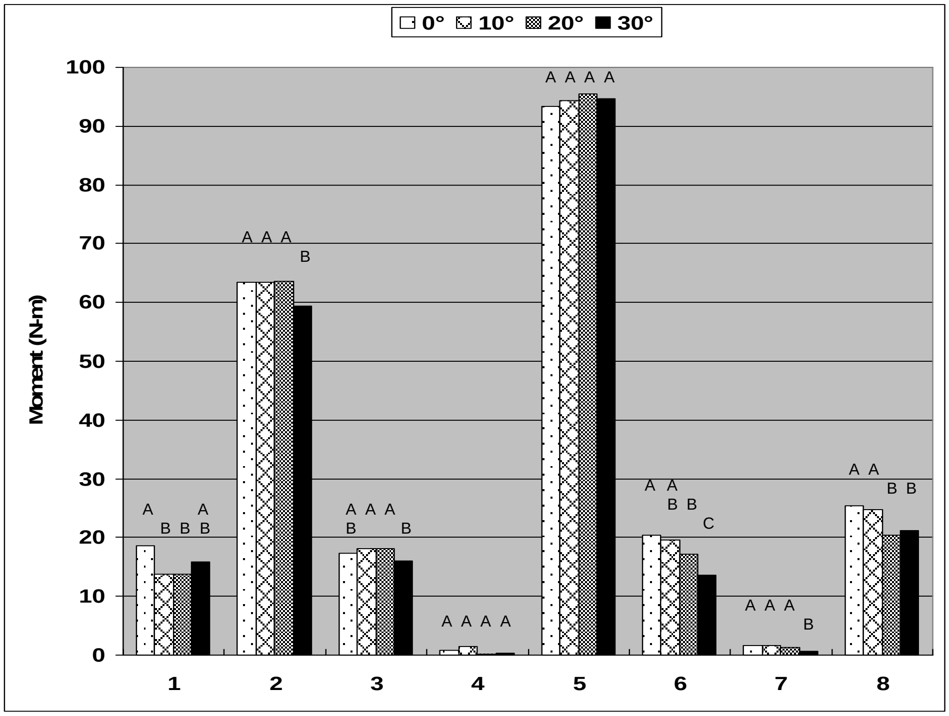

Figure 4. Components of peak L5/S1 moments as a function of lateral slant angle. 1 - Moment at shoulder joint; 2 - Moment generated by static vertical reaction force acting on shoulder joint; 3 -Moment generated by dynamic vertical reaction force acting on shoulder joint; 4 - Moment generated by horizontal dynamic reaction force acting on shoulder joint; 5 - Moment generated by gravitational force acting on trunk; 6 - Moment generated by dynamic vertical force acting on trunk; 7 - Moment generated by horizontal dynamic force acting on trunk; 8 - Moment of inertia of torso about L5/S1 joint x angular acceleration of the trunk.

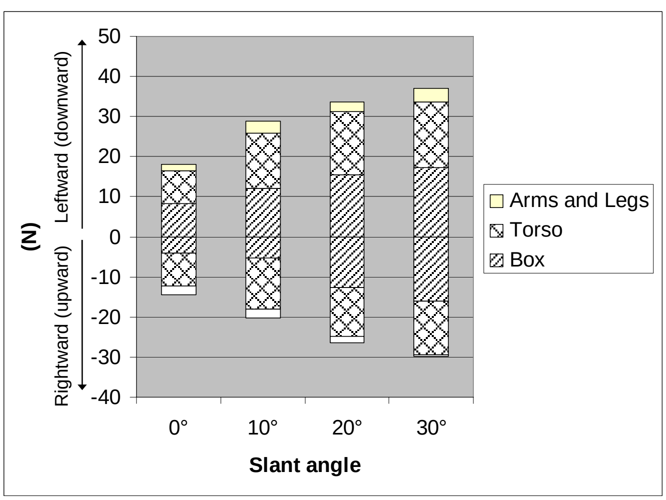

Figure 5. Overall and component analysis of peak lateral forces as a function of lateral slant angle.

DISCUSSION

As part of our on-going ergonomic intervention research in the agriculture industry, we have been focused on the evaluation of the challenges that this outdoor work environment presents. Observation of field workers in agriculture revealed a considerable amount of lifting performed on both sloped (sagittally) and slanted (laterally) ground surfaces. Previous work has illustrated changes in lifting biomechanics in response to altered slope angle (Shin and Mirka, 2004) and varied knee angle effects (Shin et al., 2004) but these works were limited to these effects in the sagittal plane. The focus of the current work was on the lateral slant scenario.

It was observed that the peak L5/S1 moment gradually decreased with slant angle increasing from 0° to 30° (Figure 3). By decomposing the peak L5/S1 moment (Figure 4), it was found that the dynamic components were most influential in the overall L5/S1 moment. This would indicate that the subjects took a more cautious approach to lifting as the standing surface angle increased because of a perception of increased instability on slanted standing surfaces. This alteration in lifting kinematics is quite different than that shown by Shin and Mirka (2004) in their study of sloped surfaces. In the component analysis of this previous study, the results showed that the changes in the peak L5/S1 moments were primarily due to alterations in the postures assumed. They attributed the changes in the postures to fundamental length-tension relationships and limitations in the range of motions of the joints of the lower extremities. The lack of consistent changes in the postures assumed in the current study would indicate that these same effects were not major contributors to the overall response, but that perceptions of stability and safety may have led to alterations in the dynamics of the lifting profile. The effects of Angle on the peak net lateral forces would indicate that this perception of instability may be driven by afferent sources that are able to provide feedback that indicate a potentially unsafe scenario is developing.

There are a number of limitations to the generalizabilty of these results that should be noted. First of all, all subjects had no experience on manual material handling on lateral ground surfaces prior to the experiment. This factor might have added to the caution that was taken by subjects during lifts. More experienced workers tend to have developed skills leading to faster lifting speed and less precaution. Therefore, it is more appropriate to apply the results of this study to new workers (e.g. under training) in such a work environment. Secondly, the lifting task performed in this lab setting utilized a platform with a high coefficient of friction, thereby keeping the risk of a slip event relatively low. In more realistic outdoor work environments, the coefficient of friction of the ground surface is likely much lower thereby making the results of this study the “best case scenario” for this kind of task. The likely result of more realistic ground surfaces would be an even greater level of caution by the lifter resulting in greater levels of co-contraction and further decreases in the speed of the lifting motion. A third important limitation of this work is the relatively short duration of the experimental lifting bout. With longer exposures to a repetitive lifting task, fatigue of the back extensors can lead to reduced neuromuscular control and greater variability in the lateral motions of the torso (Parnianpour et al., 1988). On a horizontal ground surface these lateral forces can be overcome with some effort from the lower extremities, however, on a slanted surface this corrective action is compromised, particularly if the deviation is towards the downward slope.

CONCLUSIONS

The objective of this study was to quantify the effect of laterally slanted ground surfaces on the lifting kinematics. The results showed that the peak L5/S1 moment decreased (9%) with increased slant angle, a result that was shown through component analysis to be primarily the result of decreased trunk extension acceleration. The analysis of the side-to-side motions during lifting trials indicated a significant increase (111%) in the peak net lateral force with increasing slant angle, further emphasizing the loss of stability on these slanted surfaces. The concerns related to the loss of stability when lifting on laterally slanted surfaces is certainly not a new concept, however, the results of this study provide the empirical data needed to quantitatively describe the human performance response to these conditions in terms of the changes in lifting kinematics.

ACKNOWLEDGEMENTS

This work was supported by Grant No. U50 OH07551 from the National Institute for Occupational Safety and Health (NIOSH). The contents are solely the responsibility of the authors and do not necessarily reflect the views of NIOSH.

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