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A study of lifting tasks performed on laterally slanted ground surfaces

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Lifting in most industrial environments is performed on a smooth, level ground surface. There are, however, many outdoor work environments (e.g. agriculture and construction) that require manual material handling activities on variable grade ground surfaces. Quantifying the biomechanical response while lifting under these conditions may provide insight into the aetiology of lifting-related injury. The aim of the current study was to quantify the effect of laterally slanted ground surfaces on the biomechanical response. Ten subjects performed both isometric weight-holding tasks and dynamic lifting exertions (both using a 40% of max load) while standing on a platform that was laterally tilted at 0, 10, 20 and 30° from horizontal. As the subject performed the isometric exertions, the electromyographic (EMG) activity of trunk extensors and knee extensors were collected and during the dynamic lifting tasks the whole body kinematics were collected. The whole body kinematics data were 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 of the isometric weight-holding task show a significant ($p < 0.05$) effect of slant angle on the normalized integrated EMG values in both the left (increase by 26%) and right (increase by 70%) trunk extensors, indicating a significant increase in the protective co-contraction response. The results of the dynamic lifting tasks revealed a consistent reduction in the peak dynamic L5/S1 moment (decreased by 9%) and an increase in the instability producing lateral forces (increased by 111%) with increasing slant angle. These results provide quantitative insight into the response of the human lifter under these adverse lifting conditions.

Keywords: Asymmetric lifting; Surface angle; Biomechanical model; Slant; Slope; Slip

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1. Introduction

A lifting task can be characterized by a number of task-related variables, such as the magnitude of the load, the three-dimensional location of the origin and destination of the lift, lifting speed, lifting frequency, load coupling, lifting technique and more general environmental factors (temperature, humidity, ground surface characteristics, etc.). Many of these task variables are dictated by the specific lifting task to be performed (e.g. three-dimensional location of the load, load magnitude), others may be at the discretion of the lifter (lifting technique, lifting speed) and still others may be variables that influence the techniques chosen by the lifter (e.g. lift frequency, environmental conditions). It is this third category that is the focus of the current study. Although the kinematics of body segments and joints can be self-selected and controlled by the lifter, it is believed that external environmental characteristics, such as uneven ground surface, may also influence the technique (both gross characteristics such as stoop vs. squat as well as more subtle changes in kinematic profiles and muscle co-activation strategies) as the lifter seeks to maintain stability and perform the lift safely. Understanding the nature of these changes and developing a quantitative description of these changes may provide the basis for appropriate ergonomic interventions and is the focus of the current work.

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. Previous research has shown that a sloped (forward/backward in the sagittal plane) ground surface can result in a 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.* (1987) simulated fruit-growing fieldwork to assess the influence of a sloped ground surface angle on slip risk. While subjects were lifting a weight on inclined slopes (15 and 25° in sagittal plane) and a flat surface, the foot reaction force and the path of centre of body weight were measured. The results showed that slip potential, assessed by horizontal reaction force, was significantly higher on the sloped surface and the positional variation of the body centre was less with back lifting. They also noted that the motion of the centre 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.* (2003) investigated the standing balance in construction workers during roof work. The postural sway in the anterior–posterior direction and lateral–medial direction was measured by a force plate while the subject was standing on a declined slope (from 0 to 34° in sagittal plane). Slope angle showed significant effects on the postural sway in the anterior–posterior direction and the velocity of sway. 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 (2004) investigated the effects of sloped (forward/backward) ground surface on lifting performance. 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 an increasing trend as surface angle increased from 0° to upward 20°. The postural adaptation of the body to keep the whole body balanced on a 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. Lifting on a laterally slanted

surface, which is widely observed among agriculture, construction and railroad workers, 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. Even when the lifting motion is maintained in the mid-sagittal plane, the muscle activation patterns may not be symmetric. Previous research has shown that the knee flexion angle can affect the trunk extensor muscle activation level (Shin *et al.* 2004). Changes in the knee flexion angle induce more pelvis rotation (Dewberry *et al.* 2003) resulting in less tension in spinal ligaments and this can lead to a reduction in the passive contribution of these tissues to the net trunk extension moment. To maintain static equilibrium the reduction of the passive contribution will necessitate more force from the active component – the trunk extensor musculature. The asymmetric knee flexion angle that would result from standing/lifting on a laterally slanted surface could have a direct impact on these biomechanical responses. If the standing surface is slanted from right (up) to left (down) the knee flexion angle of the right leg is larger than the left knee angle and this may entail larger activation of right side trunk extensors.

The aim of this study was to quantify the effects of a laterally slanted ground surface on the back extensor muscle activation strategies and lifting kinematics, which may provide insight into the aetiology of lifting-related injuries, especially among those aforementioned professions. It was hypothesized that, because of the pseudo-asymmetric posture that results from the slanted ground surface, the contralateral lumbar extensors would increase activation while the ipsilateral lumbar extensors would maintain a constant activation level as a function of slope angle. It was also hypothesized that the lifting kinematics would be altered to reduce the speed of the lifting motion and thereby reduce L5/S1 moment. Finally, it was 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.

2. Methodology

2.1. Subjects

Seven male and three female subjects were recruited from the university community. The subject group had a mean age of 28 (SD 3.6) years, height 174 (SD 5.9) cm and body mass 71.3 (SD 12.5) kg. All subjects were free from chronic and current back injury and gave written consent after being informed of the nature and potential risks of the experiment.

2.2. Apparatus

2.2.1. Experimental task. A platform was built that provided a ground surface that could be adjusted to the four levels of lateral slant (0, 10, 20 and 30°) of the ground surface (figure 1). The platform surface was plywood and it was covered with a cloth matting material that provided a high coefficient of friction for the lifter. Subjects lifted a 0.3m x 0.3m x 0.3m wooden box with cut-out 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.

2.2.2. Data collection. Six pairs of surface Ag-AgCl electrodes (Model E22x, In-Vivo Metric CA, USA) were used to collect the electromyographic (EMG) muscle activity of

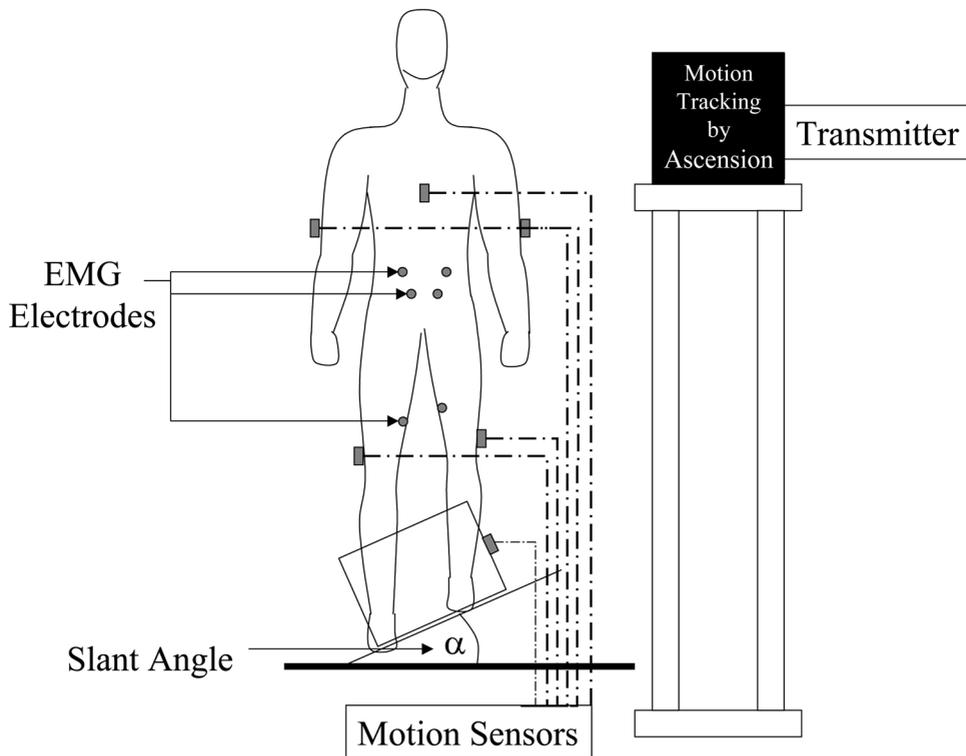


Figure 1. Coronal plane view (from the rear) of the experimental lifting environment. EMG = electromyographic.

the sampled muscles. These data were pre-amplified (1000x) and then carried via shielded cable to the main amplifiers that filtered (notch filter of 60 Hz and low pass 1000 Hz) and further amplified (50x) the EMG data. An isokinetic lumbar dynamometer (Marras and Mirka 1989) was used to provide the necessary static resistance for the collection of the angle-specific maximum voluntary contraction (MVC) EMG data from the lumbar extensors. This dynamometer system was also able to provide a measure of the angle-specific peak moment generated by the subject, necessary for the calculation of the 40% hand-held loads. The MVC force and EMG were measured at 60° trunk flexion posture and the maximum extension moment was calculated from the force data and the subject's anthropometry.

Six motion sensors from a magnetic field-based Flock of Birds motion tracking system (Ascension Technology Corporation VT, USA) 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.

2.3. Independent variables

The independent variable in this study was the lateral ground slope angle (Angle) and had four levels: 0°; 10°; 20°; and 30°. When the surface was slanted, it was always tilted to the left, meaning that the left foot was always lower than the right.

2.4. Dependent variables

The dependent variables for the static weight-holding trials included the normalized integrated EMG data of two locations on the lumbar erector spinae. The first location was 1.5 cm from the vertebral midline at the level of L4 (bilateral multifidus). The second location was 3.5 cm from the midline of the spine at the L2 level (bilateral longissimus). While the signal collected from these two trunk extensors almost certainly contained cross-talk from adjacent trunk extensors muscles, the electrode placement locations were chosen to maximize the contribution of the named muscle based on the relative cross-sectional areas of the muscles in the region (L2 ~ L4). The final two electrode pairs were placed over the bilateral vastus medialis, locating these electrodes over the belly of the muscle 9 cm above the knee joint cleft (figure 1). The dependent variables for the dynamic lifting trials were the peak L5/S1 moments for each lifting motion and peak net lateral forces (both rightward and leftward). All of these variables for the dynamic trials were calculated using a dynamic biomechanical model (introduced later) that utilized the data from the motion analysis system.

2.5. Experimental procedures

All subjects began with a stretching and warm-up period and this was followed by the placement of the surface electrodes using double-sided adhesive tape. After electrode placement the maximum voluntary trunk extension exertion was measured using a lumbar dynamometer (Mirka and Marras 1993) while the subject was at 60° forward flexion trunk angle (sagittally symmetric). A stationary chair and harness system that provided static resistance was used to gather the maximum voluntary exertion of the vastus medialis muscles. A 1-min break was given between maximum exertions. All maximum exertions lasted for 3 s. A 5-min break was given before data collection began.

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. The subject first performed the static weight-holding trials. During these trials the subject held the load in a position such that the box was level and the height of the hands was kept at the height of the left knee. This was held constant across levels of Angle so that the necessary degree of trunk flexion was held constant so as not to be a confounder in the analysis. Each level of Angle was repeated five times and the trial order was fully randomized. One experimenter always supervised and assisted the subject before data collection to ensure that the location of the load was held at a constant height across trials. Short breaks were frequently provided during the experiment to prevent any possible discomfort or fatigue in subjects.

After the static weight-holding trials were completed, surface electrodes were removed and six motion sensors were placed on the lateral projection of the centre of mass of both upper legs, lateral projection of the centre of mass of both arms, posterior side upper back at T9 and on the lateral side of the centre of the box (figure 1). After the motion sensor placement, subjects stood on a flat surface and performed two or three freestyle lifts while movements were collected and analysed briefly to verify sensor assignment and orientations. After a 1-min break, the dynamic lifting trials began. Each trial was performed under one level of Angle and lasted for 40 s, during which subjects performed five repetitive freestyle lifts (8 s each). In each lift, subjects started from a 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 their

arms straight. When the subject's 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 signal ('lift'). There were a total of eight dynamic lifting bouts (four surface angles and two repetitions for each angle) and the order of trials was randomized. There was a 15-s rest break between consecutive trials, during which the platform slant angle was adjusted to the next setting. Special attention was paid to make sure that the projection of the subject's both ankles cast on the platform was at the same location throughout the experiment and that the centre of the load was on the subject's sagittal plane. Therefore, the distance between the initial centre of the load and the subject was constant throughout the data collection.

2.6. Data processing

2.6.1. Electromyographic data. The raw data were filtered in software using a 10–500 Hz pass filter as well as a notch filter that eliminated 60 Hz and its aliases. Once filtered these signals were rectified (full-wave) and averaged across the 3 s data collection period. This processing occurred in both the data collected during the experimental trials as well as the MVCs. The EMG data collected during the maximum exertions were then partitioned into 1/8 s windows and the maximum of the 24 windows for each muscle in each posture was identified and was used as the denominator in the process of normalizing the experimental data.

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

2.7. Biomechanical models

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. Briefly, this model utilizes the data describing the angular and linear acceleration of the body segments, as well as the instantaneous body segment positions, to arrive at an estimation of the total L5/S1 moment. Each of these components that made up the L5/S1 moment were 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 was 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 Pheasant (1986) and McConville *et al.* (1980) 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 ($m \times a$) was calculated. As in the calculation of the peak L5/S1 moment, each of the components that made up the net lateral force was 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 was 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 modelling 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 8 s (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.

2.8. Data analysis

The dependent variables were then statistically analysed using ANOVA to examine the effect of Angle. The assumptions of the ANOVA were first tested and verified using the graphical approach advocated by Montgomery (2001). A p -value of less than 0.05 was used as the criterion for significant effect. A Tukey-Kramer post hoc analysis was employed when any significant difference was found by the ANOVA.

3. Results

3.1. Static weight-holding trials

The results of the analysis of the static weight-holding task showed that Angle had a significant effect on the muscle activation levels of the bilateral longissimus and multifidus

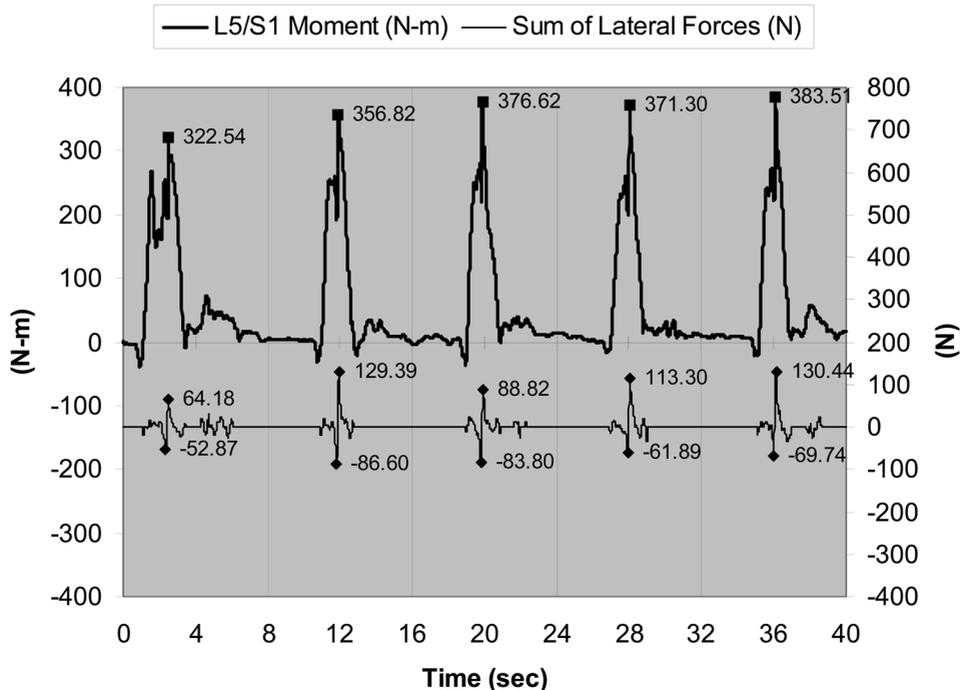


Figure 2. Illustration of the time-dependent L5/S1 moment and net lateral force. Peaks of each used in the data analysis are also identified.

and the right vastus medialis (figure 3). In general, the lumbar extensor muscle activities increased as the slant angle increased, with the exception of a slight reduction (not significant) for the left side trunk extensors at 10°. This increasing trend is more consistent and pronounced in all of the right muscles. The interpretation of this result is that the contralateral (right side) muscles followed the expected trend (increase of 70%) because of the ‘asymmetry’ of the lift, but the increase (of 26%) in the ipsilateral (left side) muscle was not expected and illustrates a general increase in the co-contraction response.

3.2. Dynamic lifting trials

3.2.1. Peak L5/S1 moment. 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 4). In the analysis of the components that comprised this peak moment value, it was 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 5), 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.

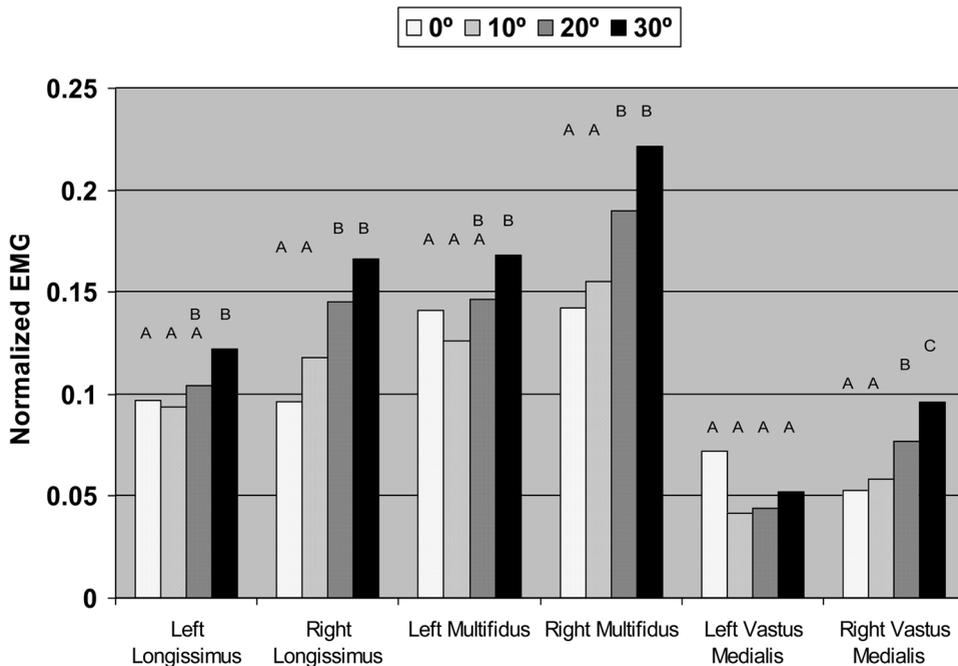


Figure 3. Effect of lateral slant angle on muscle activity during static weight-holding task. The letters above each column are from the Tukey-Kramer post hoc test. Different letters represent angles that are statistically different from one another. EMG = electromyography.

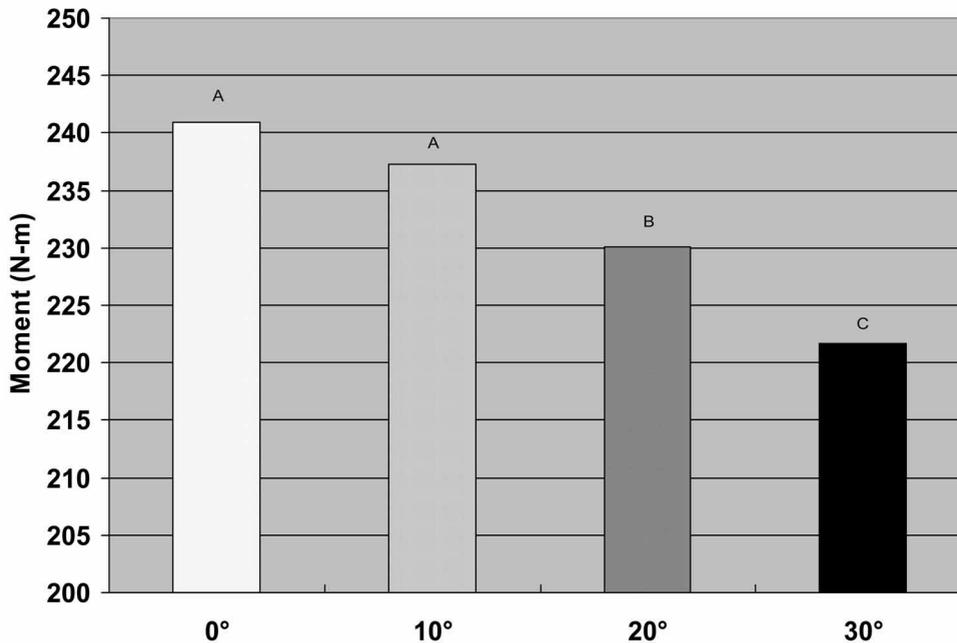


Figure 4. Peak L5/S1 moments as a function of lateral slant angle.

3.2.2. Peak lateral forces. The analysis of the net lateral force results showed that increasing level of Angle generated a 111% increase in the peak lateral forces (figure 6). 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 leftward forces (down the slant) were shown to be consistently larger than the rightward forces across all angles ($p < 0.05$).

4. Discussion

As part of the ongoing ergonomic intervention research in the agriculture industry, this research group has 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 and carrying performed on non-horizontal work surfaces. This includes both sloped (forward/backward) and slanted (side-to-side) ground surfaces. It is logical to consider that these ground surface orientations can alter the normal biomechanics of the lifting motion, as changes in the lower extremity positioning (and resulting impact on the biomechanics of the torso) can be considerable. Previous work has illustrated some of these important changes in response to altered slope angle (Shin and Mirka 2004) and varied knee angle effects (Shin *et al.* 2004) but these previous works were limited to these effects in the sagittal plane. The focus of the current work turned the orientation of the human lifter 90° and focused on the lateral slant scenario.

As has been hypothesized, activation levels of the trunk extensors showed an asymmetric response to surface angle. The main postural difference between the left and right side during static weight-holding trials was the flexion of the right knee and much of

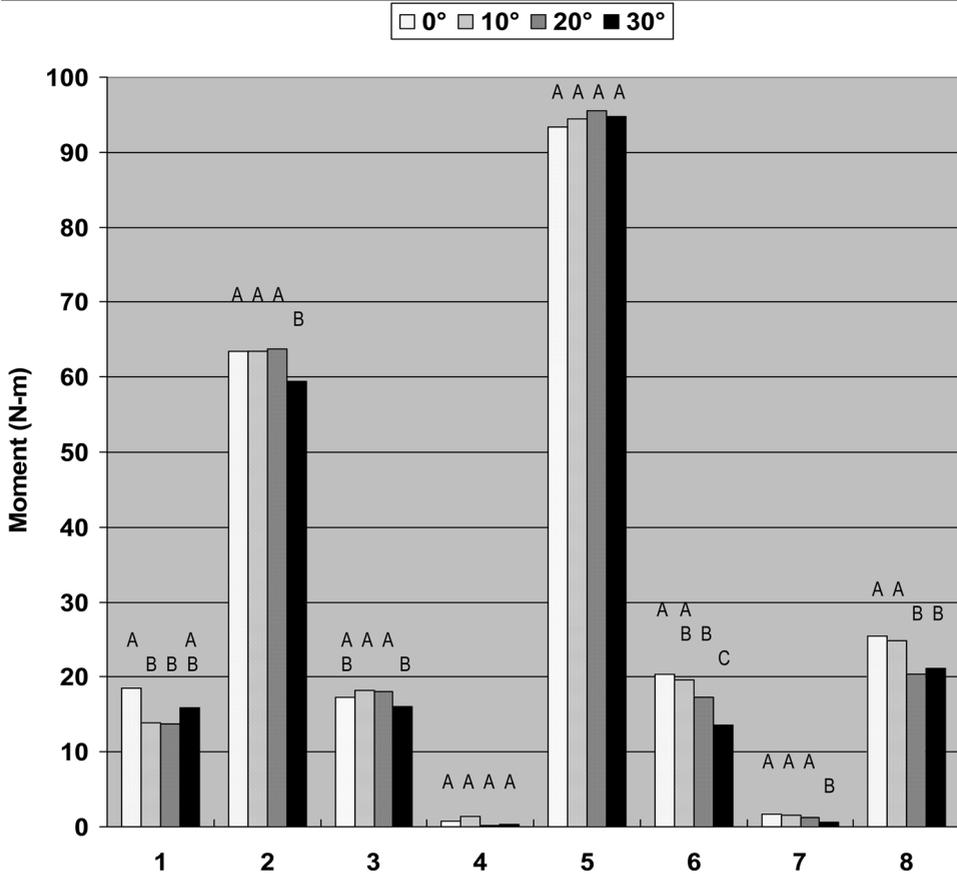


Figure 5. Components of peak L5/S1 moments as a function of lateral slant angle. 1, Moment at shoulder joint; 2, moment generated by static vertical reaction force acting on shoulder joint; 3, moment generated by dynamic vertical reaction force acting on shoulder joint; 4, moment generated by horizontal 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.

the asymmetric response of the trunk extensor was attributed to this differential in knee flexion angle. A recent study (Shin *et al.* 2004) examined the effect of knee angle and lumbar flexibility on muscle activities of trunk extensors during static weight-holding trials. It was observed that the knee flexion increased the activity of the trunk extensors and it was hypothesized that this was due to a reduction in the moment producing capacity of the passive tissues. Similarly, in the present study, the right side extensors showed increasing activity with greater slant angle. The relative magnitude of the normalized EMG values lends some support to this passive tissue hypothesis in that they were typically in the range of 10–20% of max while the load being lifted was calculated to be 40% of max, indicating that there may have been a significant contribution of the passive extensor mechanism to the total moment. Therefore, the knee angle response seen

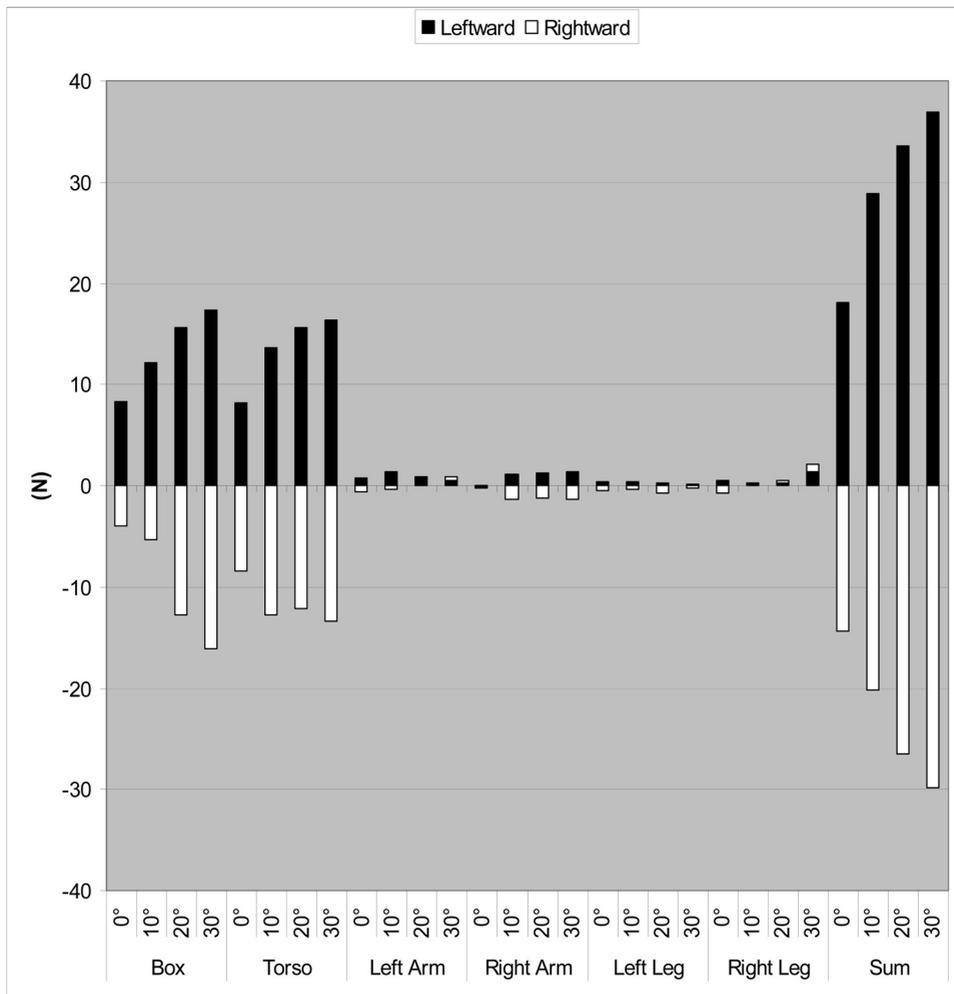


Figure 6. Overall and component analysis of peak lateral forces as a function of lateral slant angle.

in Shin *et al.* (2004) may be playing an active role in the responses seen in the current study.

This biomechanical logic helps to explain the increases in the activation of the contralateral (i.e. uphill or knee bent side) trunk extensor musculature, but what was not expected was that increasing the lateral slant angle generated more co-activation of the ipsilateral (i.e. downhill or knee straight side) trunk extensors as well. The results show that there was a slight (not significant) reduction in the activity of the left (ipsilateral) trunk extensors in going from 0 to 10° but, beyond that value, the ipsilateral trunk extensors increased, indicating a co-contraction strategy presumably to maintain torso stability. It can be concluded from these results that when workers have to perform lifting tasks on a slanted surface, their back muscles have to work harder to accommodate for the uneven lifting surface, which increases the risks of musculoskeletal disorders of the low back. Most interestingly, such risks could be asymmetric since the extensor muscles

on the side of the elevated leg are the most affected, although there is a general increase in muscle co-contraction as well.

It was observed that the peak L5/S1 moment gradually decreased with slant angle increasing from 0 to 30° (figure 4). By decomposing the peak L5/S1 moment (figure 5), 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. The response of the extensor muscle activity would be consistent with the results that have shown increases in muscle co-contraction under conditions of instability (e.g. van Dieen *et al.* 2003, Granata *et al.* 2004). Therefore, providing aids to reduce the sense of instability may help lower muscle co-contraction levels and thereby reduce the risk of musculoskeletal disorders.

There are a number of limitations to the generalizability of these results that should be noted. First, the lifting task performed in this laboratory 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 second 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. A third limitation factor resulted from allowing subjects to choose their preferred footing during experiments, which may not be the case in some more realistic work environments due to task requirements or restricted ground space. With their feet in awkward positions, lifters may have a different range of motion for joints of lower extremity and thereby adopt different lifting strategies (e.g. muscle activation patterns, lifting technique and speed, etc.) than what was observed in this study. The last limitation is the relatively small slant angle and overall low height level of the platform utilized in the experiment. Some professions (e.g. construction) may find lifters perform tasks at a larger slant angle or even at a height well above the ground, where awareness of much greater risks of slip or fall, through both physical and cognitive means, could greatly impact the way lifting is performed (Holmstrom *et al.* 1992). It can be noted that the limitations mentioned above

all resulted from reduction of some of the real world effects during the experimental set-up.

5. Conclusions

The objective of this study was to quantify the effect of laterally slanted ground surfaces on the biomechanics of lifting. The results of the isometric weight-holding task showed an increase in both the contralateral (70% increase) and ipsilateral (26% increase) trunk extensor muscle groups with increasing slant angle, indicating increases in the general levels of co-contraction to increase trunk stability. Consistent with these concerns related to trunk stability, the results of the analysis of the lifting kinematics from the dynamic lifting trials 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 these dynamic 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 and muscle activation/co-activation strategies.

Acknowledgements

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