Ergonomics
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713701117

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To cite this Article Shin, Gwanseob and Mirka, Gary(2004) 'The effects of a sloped ground surface on trunk kinematics and L5/S1 moment during lifting', Ergonomics, 47: 6, 646 — 659

To link to this Article: DOI: 10.1080/00140130310001653066

URL: http://dx.doi.org/10.1080/00140130310001653066

ERGONOMICS, 15 MAY, 2004, VOL. 47, NO. 6, 646–659

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The effects of a sloped ground surface on trunk kinematics and L5/S1 moment during lifting

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Keywords: Lifting technique; Slope; Biomechanical model; L5/S1 joint moment

There are many work environments that require workers to perform manual materials handling tasks on ground surfaces that are not perfectly flat (e.g. in agriculture, construction, and maritime workplaces). These sloped ground surfaces may have an impact on the lifting strategy/technique employed by the lifter, which may, in turn, alter the biomechanical loading of the spine. Describing the changes in kinematics and kinetics of the torso is the first step in assessing the impact of these changes and is the focus of the current research. Subjects' whole-body motions were recorded as they lifted a 10 kg box while standing on two inclined surfaces (facing an upward slope: 10° and 20°), two declined surfaces (facing a downward slope: $-10°$ and $-20°$), and a flat surface (0°) using three lifting techniques (leg lift, back lift and freestyle lift). These data were then used in a two-dimensional, five-segment dynamic biomechanical model (top-down) to evaluate the effect of these slopes on the net moment about the L5/S1 joint. The results of this study showed an interesting interaction effect wherein the net L5/S1 moment was relatively insensitive to changes in slope angle under the back lift condition, but showed a significant effect during the leg lift and freestyle lifting conditions. The results show that under the freestyle lifting condition the peak L5/S1 moment was significantly higher for the inclined surfaces as compared to the flat surfaces (6.8% greater) or declined surfaces (10.0% greater). Subsequent component analysis revealed that both trunk flexion angle and angular trunk acceleration were driving this response. Collectively, the results of this study indicate that ground slope angle does influence the lifting kinematics and kinetics and therefore needs to be considered when evaluating risk of low back injury in these working conditions.

1. Introduction

Low back pain (LBP) is recognized as one of the most common medical conditions in the western world, affecting up to 85% of the population sometime during their lifetime (Von Korff *et al.*, 1988; Andersson, 1998). LBP is the second most frequently reported reason for a physician visit, the fifth most frequent cause of hospitalization, and the third most frequent reason for a surgical procedure (Andersson, 1998). In 2000, nearly 5.7 million cases were reported as non-fatal occupational injuries and illnesses in private industry and over 410 000 cases were back and spine injuries (Bureau of Labor Statistics, 2000a,b).

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Ergonomics ISSN 0014-0139 print/ISSN 1366-5847 online
http://www.tandf.co.uk/journals
DOI: 10.1080/00140130310001653066

There are a number of recognized occupational risk factors for low back pain including high force trunk exertions (Xu *et al.*, 1997), awkward trunk postures (Liira *et al.*, 1996), repetitive lifting (Kraus *et al.*, 1997), dynamic lifting (Marras *et al.*, 1995), and exposure to vibration (Liira *et al.*, 1996). Posture and trunk kinematics are two risk factors that are influenced by the lifting strategy (whole body posture, lifting speed, etc.) employed by the lifter to perform a particular lifting task and the development of this strategy may be the result of the lifter's perceptions of risk of injury (e.g. high muscular stress, whole body instability, local joint stress or instability). Whatever the source, these changes in lifting kinematics can have a profound effect on the biomechanical loading of the spine and understanding how characteristics of the lifting environment influence the kinematics is important information that can impact workplace design and risk of work-related low back injury.

The slope of the ground surface on which the lifter is standing is one variable that could logically influence the strategy of the lifter. Concerns with regard to whole-body stability and slip potential could change the posture and motion profile of the lifter. Zhao *et al.* (1987) observed the potential risks of slipping during manual material handling in agricultural activities particularly manual lifting in fruit and vegetable growing fields. To investigate slip potential during lifting while standing on inclined surfaces, they asked eight subjects to perform leg lifts and back lifts on the two inclined surfaces (15° and 25°), while they recorded the path of the weighted box and ground reaction forces. Subjective ratings of slip potential were also reported. Ground reaction force data showed that increased slope angle (from 15° to 25°) increased the risk of slipping significantly. In the analyses of the subjective data, subjects confirmed the ground reaction force data by stating that they perceived that lifting on the 25° inclined slope was more risky than lifting on 15° inclined slope. These results would indicate a potentially important perceptual aspect of these tasks that could impact the technique (postures and dynamics) employed by the lifter.

Another body of literature pertinent to this discussion is the literature related to the standing or walking with high-heeled shoes. Since wearing high-heeled shoes causes the similar ankle angle changes to those seen when a person is standing on declined slopes, research investigating the effects of this kind of footwear on posture kinematics is of some relevance. Opila *et al.* (1988) and Franklin *et al.* (1995) studied the postural difference in barefoot and high-heeled shoes and observed that the heel inclination caused lumbar flattening, a backward tilting pelvis, a reduction of the distance of the knee and ankle from the line of gravity, and a posterior displacement of the head and thoracic spine. They reasoned that these postural changes might be due to a tendency to overcompensate for the sensation of falling forward caused by the raised heels. Extrapolating these results to a lifting task on a sloped surface, it is logical to hypothesize that lifting kinematics would be altered on sloped surfaces due to changes in perceived whole-body stability. Ultimately these altered lifting kinematics would have an effect on the biomechanical loading of the spine.

In addition to ground surface slope angle, lifting technique (back lift, leg lift, freestyle, etc.) has been studied to better understand its influence on trunk posture and trunk kinematics during lifting activities (see van Dieen *et al.* (1999) for an extensive review of this topic). The leg lift technique (squat lift) generally involves much larger flexion of knee joint and less flexion of hip/lumbar joints than does the back lift (stoop lift) wherein the knees remain relatively straight and lowering of the center of gravity is accomplished more by the flexion of the lumbar spine and the hip.

Given that the perceived, whole-body postural stability can be influenced by the perceived stability of the ankle and knee joints, quantifying the interactive effects of ground slope angle and lifting technique on trunk posture and kinematics during a lifting task is necessary and will most likely provide more insight than considering ground slope angle alone.

The main objective of this study was to examine effects of ground surface slope, lifting technique, and their interaction on the kinematics and kinetics of the torso during lifting activities and to evaluate the underlying root cause of these responses through an analysis of the individual components of the total L5/S1 moment. It is hypothesized that sloped ground surfaces will create a less stable lifting environment which will tend to create slower lifting motions but that this response could be modified by the lifting technique employed specifically that the influence of slope angle would be less in the back lift technique than in either the leg lift or freestyle lift technique. These results could have important implications in the design of lifting activities in environments with uneven terrain.

2. Methodology

2.1. *Participants*

Seven men and six women (age: range 23 – 34 years, mean 28.5 years; stature: range 1.55 – 1.81 m, mean 1.69 m; whole body mass: range 50 – 111 kg, mean 64.9 kg) were recruited from the university community and participated voluntarily. None of the subjects had current or chronic complaints in the back or knees, and all gave written informed consent before participation.

2.2. *Apparatus*

In this experiment, participants lifted a wooden box (35 × 35 × 30 cm) that had a mass of 10 kg. A wooden platform was developed that could be adjusted to create an inclined (toes raised) or declined (toes lowered) standing work surface. High-friction material was secured on the surface to prevent slipping. The horizontal and vertical distance between the ankle joint and initial position of the box were kept constant across all trials. The vertical distance from the ankle to the box handle was set at 21.5 cm, and the horizontal distance from the anterior end of the foot to the centre of the box was set at 21.3 cm (Figure 1) for all lifts to avoid nuisance variance due to variability in the lift starting point.

The Flock of Birds magnetic motion tracking system (Ascension Technology Corporation) was used to quantify the whole-body lifting motions of the subjects. The static positional accuracy of the system was 7.6 mm RMS (resolution = 0.76 mm RMS) at 1.52 m range and the static angular accuracy was 0.5° RMS (resolution = 0.1° RMS) at 1.52 m range. In total five sensors were used: (1) sensor one was placed on the spine over the T9 vertebra; (2) sensor two was placed on the lateral surface of the right upper extremity at the height of the centre of mass of the upper extremity (just proximal to the elbow); (3) sensor three was placed on the lateral surface of the right thigh at the centre of mass of the thigh; (4) sensor four was placed on the lateral aspect of the right leg (shank) at its centre of mass; and (5) sensor five was placed on the right side of the box to be lifted at its centre of mass. The projection of the locations of these five sensors onto the sagittal plane provided the input necessary to create the stick figure for the biomechanical model (Figure 2).

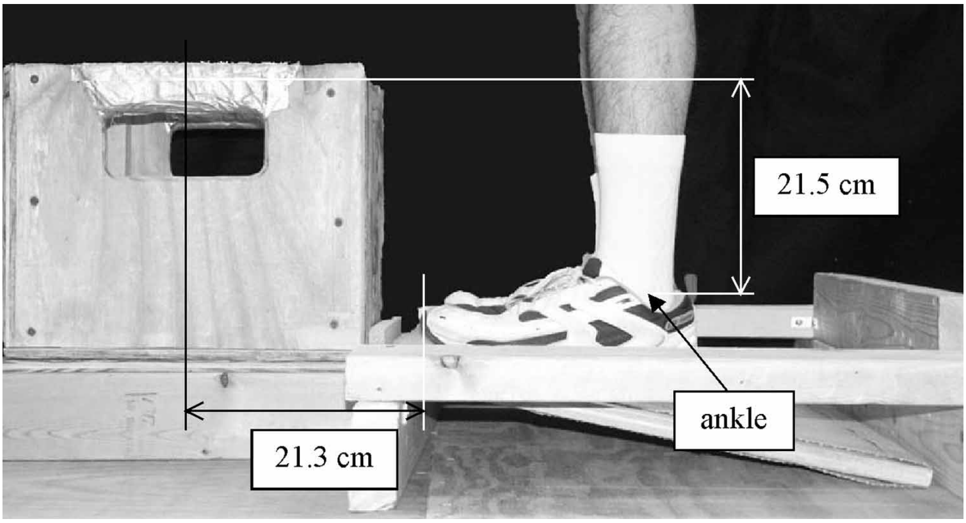

Figure 1. Experimental arrangement with the wooden platform (10° inclined slope) and box.

2.3. *Experimental design*

The independent variables in this study were slope angle and lifting technique. The slope angles included two inclined slope angles (20°, 10°), two declined slope angles (− 20°, − 10°), and horizontal ground (0°). On each of the five different slope angles subjects were asked to perform lifts with each of three lifting techniques: leg lift, back lift, and freestyle lift. During the back lift subjects were asked to keep the knees as straight as possible and flex the back. In the leg lift technique the subjects were asked to keep the back as upright as possible and flex the knees. Freestyle lift technique was self-selected and not constrained. All lifts were sagittally symmetric and the lifting motions were continuous. The order of presentation of the conditions was completely randomized.

The dependent variables in this study were the peak moment about the L5/S1 joint during the concentric lifting motion, the trunk flexion angle at the instant of the peak L5/S1 moment (ANG) and the sagittal angular trunk acceleration at the instant of the peak L5/S1 moment (ACC). The latter two of these variables were chosen (as opposed to the absolute peak values of these variables) because of their importance in the interpretation of the decomposition of the overall L5/S1 moment in the component analysis.

2.4. *Experimental procedure*

Each subject participated in a brief warm-up/stretching period followed by a training period to become familiarized with the experimental procedures and lifting techniques. Subjects performed at least five to ten lifts on a flat surface (0°) using each of the three lifting techniques to be sure that they understood how the different lifting techniques were to be performed (with feedback from the experimenter provided).

The experiment consisted of 15 lifting bouts (trials) that were 50 s in duration. Within each trial, subjects were able to perform between seven and nine lifts. The

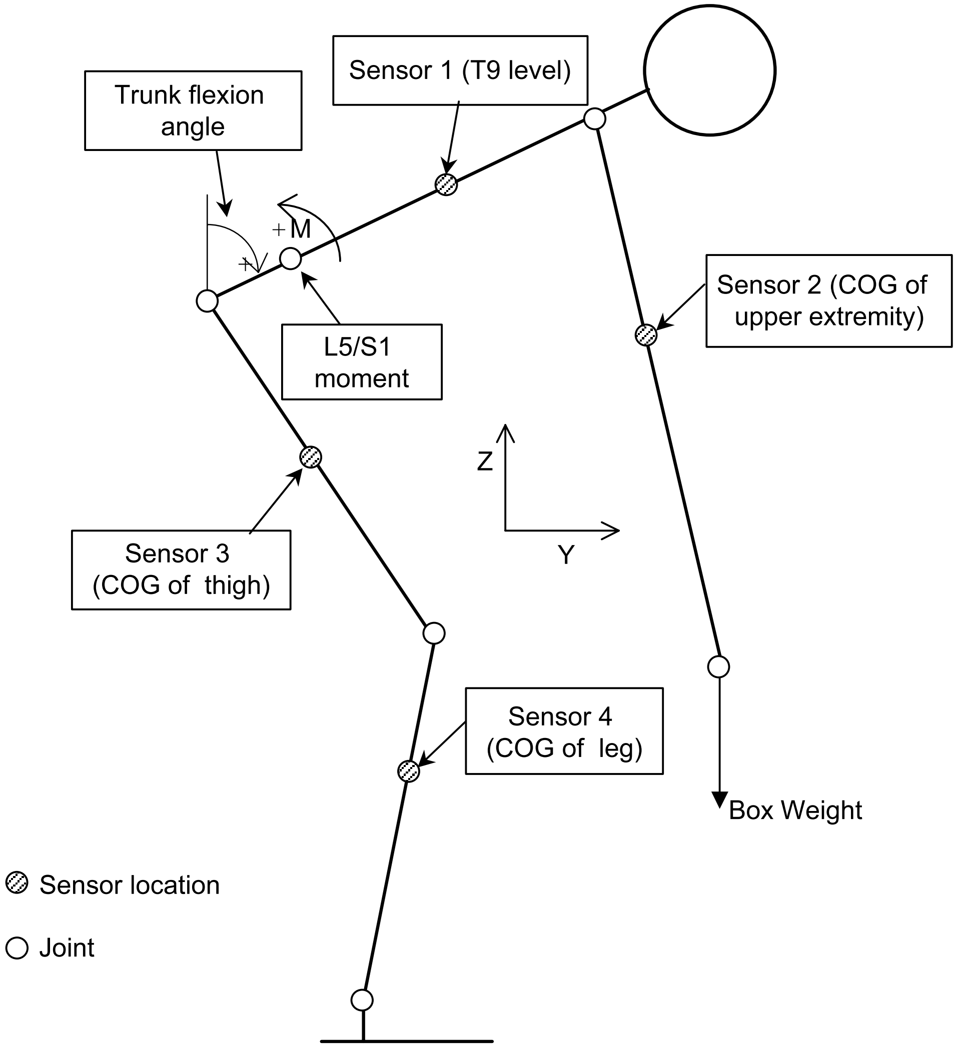

Figure 2. Five-segment, two-dimensional, sagittally symmetric lifting model.

subject started from a standing upright position and then bent down to grasp the handles of the box and lifted it to mid-thigh height as their torso returned to its original upright position. When the subject's torso returned to this upright position, the experimenter took the box and returned it to its starting position. After a 4 s pause, the experimenter gave a signal and the subject performed another lift under the same condition (same lifting technique and slope). This continued until the 50 s time limit was reached. A 60 s break was given between consecutive trials, and the platform slope angle was adjusted to the next slope setting by the experimenter. Before each trial, the subject was instructed which of three different lifting techniques was to be used in the following trial. For all lifts, the subjects were asked to lift the box at what they considered to be an average lifting speed.

2.5. *Biomechanical model*

The biomechanical model used to calculate L5/S1 moment was a two-dimensional, five-segment dynamic model (Figure 2). The body was divided into segments describing the foot, lower leg (shank), thigh, head-neck-trunk, and upper extremity (shoulder through to box handles). The upper extremity was treated as a single segment because the lifting task required subjects to lift the box only to mid thigh level and pilot studies revealed no elbow flexion during the lift, particularly in the lift-off phase wherein the peak moments typically occurred. Moments at the hand load interface were not incorporated into the model as it was assumed that the coupling between the hand and the box acted as a hinge joint, a reasonable approximation for the beginning phase of a lift. The mass of each segment, the location of centre of gravity (COG) of each segment, and the moment-of-inertia of each segment were estimated using the equations of Pheasant (1986) and McConville *et al.* (1980) and the anthropometric data gathered from each individual subject. The body segments were connected by frictionless, simple hinge joints. This top-down biomechanical model included gravitational effects for each body segment ($F = mg$), linear (horizontal and vertical) acceleration effects for each body segment ($F = ma$), as well as the rotational moment-of-inertia effect for each body segment ($M_{CM} = I_{CM}\alpha$) in computing the net moment about L5/S1.

2.6. *Data processing*

The kinematic variables captured during the lifting tasks were processed to obtain the necessary time-dependent inputs for the biomechanical models (linear and angular accelerations). The y-z coordinates and angle about the x-axis (the three data that described sagittal plane position/posture) from each of the magnetic sensors were recorded at 60 Hz. The raw data were then low-pass filtered by a second-order Butterworth filter with an effective cut-off frequency of 20 Hz. The second derivative (nine-point differentiation method, Lanczos, (1956)) of raw data yielded angular and linear accelerations. The recording, filtering, and derivation of acceleration were carried out using the Motion Monitor^{TM} Ver.4.0 (Innovative Sports Training, Inc) software. These filtered data were used in the biodynamic model and the peak L5/S1 moment value between the 'lift off' point and the 'end of lift' was identified for each lift (Figure 3). The first two lifts within each trial were not included in the statistical analyses to allow the subject to develop a steady-state lifting strategy for that specific condition (an approach confirmed in preliminary pilot work). The next five lifts in each trial were included in the statistical analysis.

2.6. *Data analysis*

The analysis of variance procedure (ANOVA) was performed on the two-factor (5×3) randomized block design (participants acting as blocks) to test for differences between the three levels of lifting technique and the five levels of slope angle. Significant effects ($\alpha = 0.05$) were further analysed using Tukey's multiple comparison test to identify the specific levels of the independent variables that generated this significance. In a follow-up analysis, the eight individual elemental moments (described in Table 1) that were summed to find the overall peak L5/S1 moment were reviewed to identify those components that contributed to any response as a function of the independent variables. Individual element moments that were highly correlated with the overall peak L5/S1 moment were considered 'drivers' of this overall response.

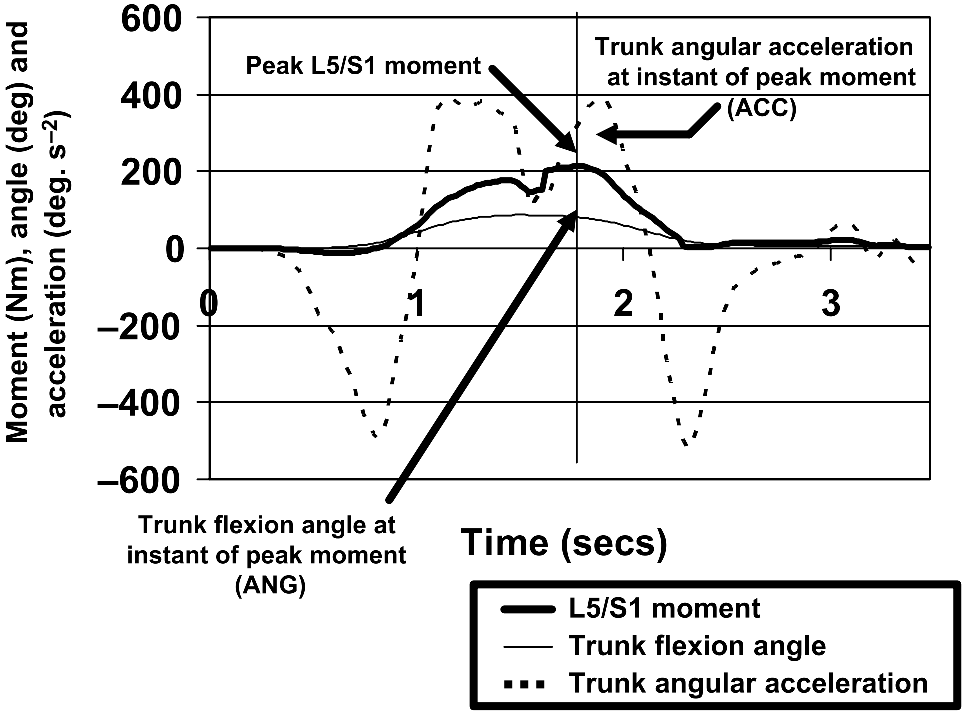

Figure 3. Time trace of L5/S1 moment and trunk angle during a freestyle lift.

Table 1. Components in the biomechanical model that contributed to the net moment about the L5/S1

Name	Descriptions
sh_m	Moment at shoulder joint
sh_vrs	Moment created by the vertical static reaction force at shoulder joint
sh_vrd	Moment created by the vertical dynamic reaction force at shoulder joint
sh_hrd	Moment created by the horizontal dynamic reaction force at shoulder joint
tr_vs	Moment created by the torso gravitational force
tr_vd	Moment created by the torso vertical dynamic inertial force
tr_hd	Moment created by the torso horizontal dynamic inertial force
torso_aa	Moment-of-inertia of torso about L5/S1 joint × angular acceleration of trunk

sh: shoulder; tr: trunk-neck-head segment; v: vertical; h: horizontal; s: static; d: dynamic; r: resultant reaction force at the joint due to forces/moments distal to the shoulder; m: resultant moment due to forces/moments distal to the shoulder.

3. Results

3.1. *Trunk kinematics*

Slope angle and lifting technique both affected ANG ($P < 0.05$) while their interaction was not found to be significant. In all three lifting techniques, the value of ANG increased as the ground surface changed from a declined to an inclined slope (Figure 4). Consistent with the results of Kjellberg *et al.* (1998), the back lift

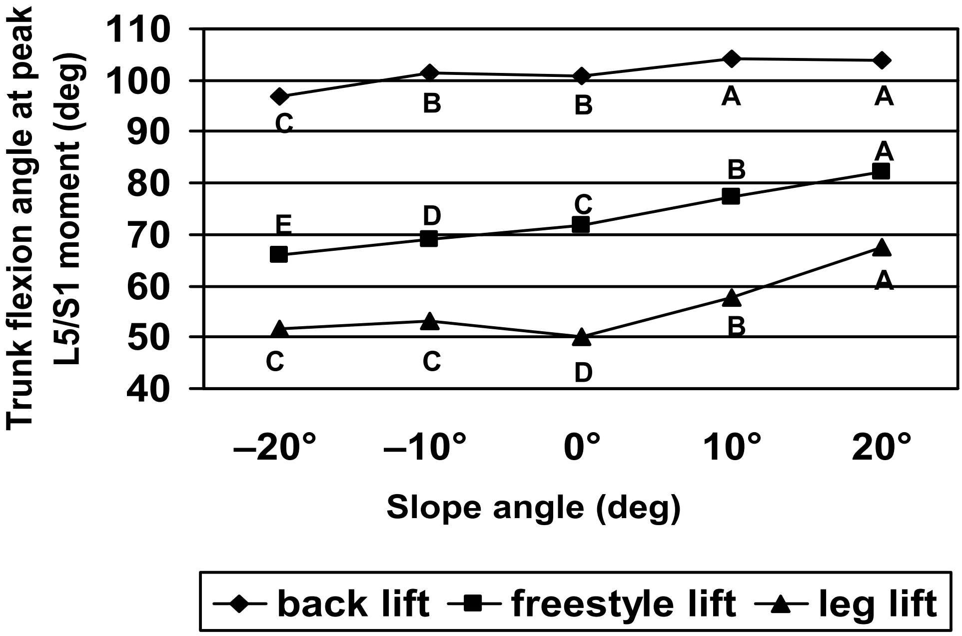

Figure 4. Trunk flexion angle at instant of peak L5/S1 moment as a function of slope angle and lifting style (Data points with different letters indicate significant differences ($P < 0.05$) in the *post hoc* Tukey's tests).

technique generated consistently higher values of this variable as compared to the other lifting techniques considered.

The effect of slope angle and lifting technique on ACC showed several interesting trends (Figure 5). The interaction between slope and technique was significant ($P < 0.05$) with the back lift showing the highest ACC on the flat surface and decreasing for both inclined and declined slopes, while ACC steadily increased from declined to inclined slopes in the freestyle condition. The effect of slope angle during the leg lifts was less consistent with the lowest ACC occurring while lifting on the inclined surfaces. The main effect of slope angle was not significant while the significant effect of lifting style ($P < 0.05$) showed that back lifts generated consistently higher ACC values that the other two lifting techniques.

3.2. *Peak L5/S1 joint moment*

When considering the peak L5/S1 joint moment, the interaction between slope angle and lifting technique was significant ($P < 0.05$) (Figure 6) with slope angle having a significant effect on the peak L5/S1 moment during the leg lift and freestyle lift but no effect during the back lift. The peak L5/S1 moment increased 6.8 and 14.3% as slope angle increased from 0° to 20° during the freestyle lift and the leg lift, respectively. The effects of lifting technique on peak L5/S1 moment showed that the peak L5/S1 moment was significantly higher in the back lift than those in the leg lift.

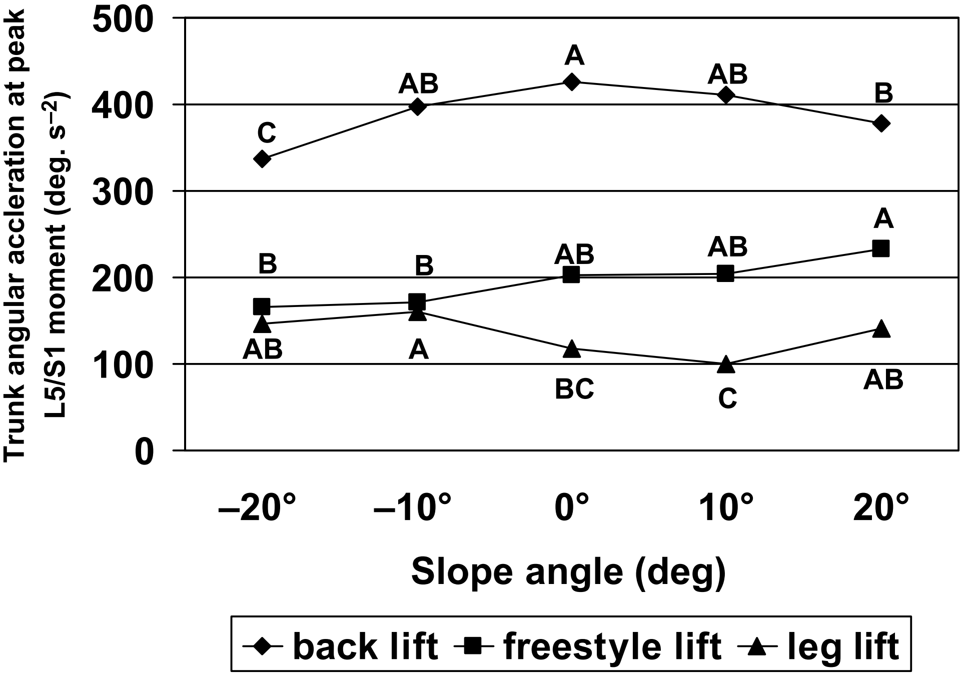

Figure 5. Trunk angular acceleration at instant of peak L5/S1 moment as a function of slope angle and lifting style (Data points with different letters indicate significant differences ($P < 0.05$) in the *post hoc* Tukey's tests).

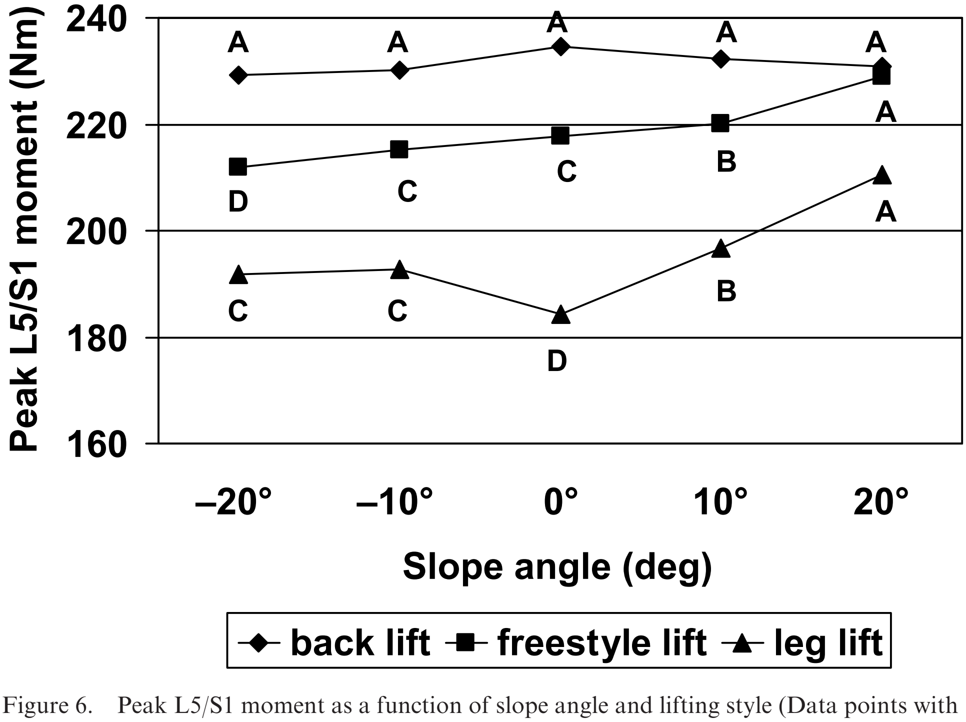

Figure 6. Peak L5/S1 moment as a function of slope angle and lifting style (Data points with different letters indicate significant differences ($P < 0.05$) in the *post hoc* Tukey's tests).

3.3. *Component analysis of the peak L5/S1 moment*

To better understand the underlying contributors to the significant effects of ground slope angle, a component analysis was performed wherein the total moment was decomposed into its constituents (Figures 7 and 8) and then the correlation between each of these constituents and the overall response was calculated. To investigate the underlying contributors in the significant effect of slope angle, data from the freestyle lift and the leg lift were analysed (the two lifting techniques that were found to be significantly affected by the slope angle). In the leg lift significant correlations ($P < 0.05$) were found between peak L5/S1 moment and two static moment components: (1) the moment tr-vs created by the gravitational force on the mass of the torso (correlation 0.98); and (2) the moment sh-vrs created by the gravitational force on the mass of the arm and box (correlation 0.97). In the freestyle lift, these same two static components were also found to be correlated ($P < 0.05$) with peak L5/S1 moment (correlations 0.92 and 0.91, respectively) but a high correlation (0.96) was also found for the moment generated through the angular acceleration of the torso (torso_aa). These results indicate that trunk flexion angle was an important underlying factor in the response of the overall L5/S1 moment as a function of slope angle for both of these lifting techniques and the effect of the angular acceleration was important in the freestyle lift.

4. Discussion

The foundation for the biomechanical approach to addressing low back injury risk is that the likelihood of low back injury depends on the magnitude of the forces/

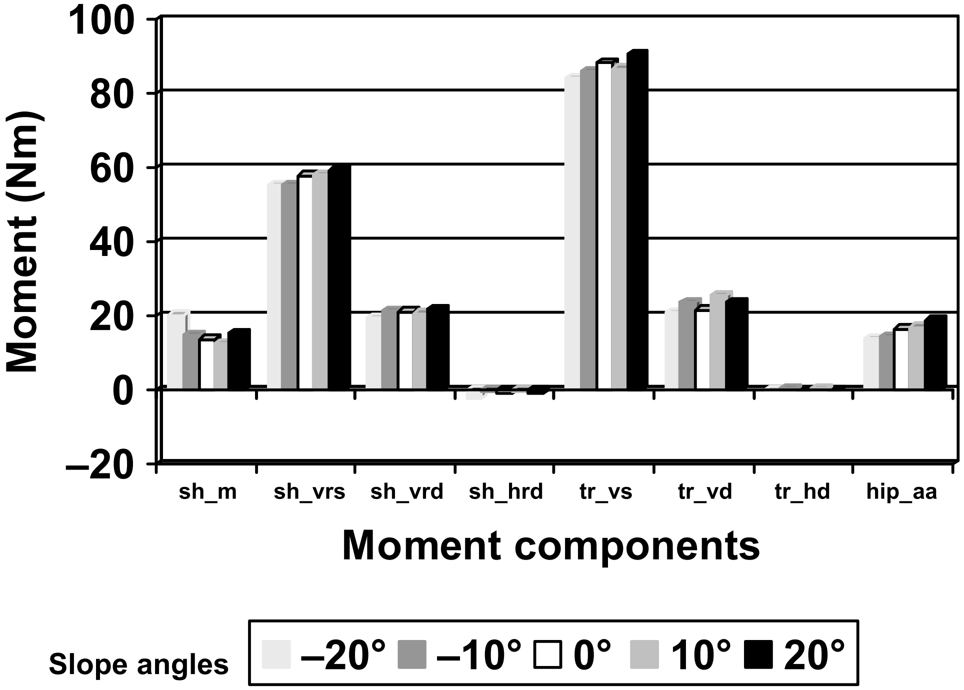

Figure 7. Component analysis of mean peak L5/S1 moments for the freestyle lift.

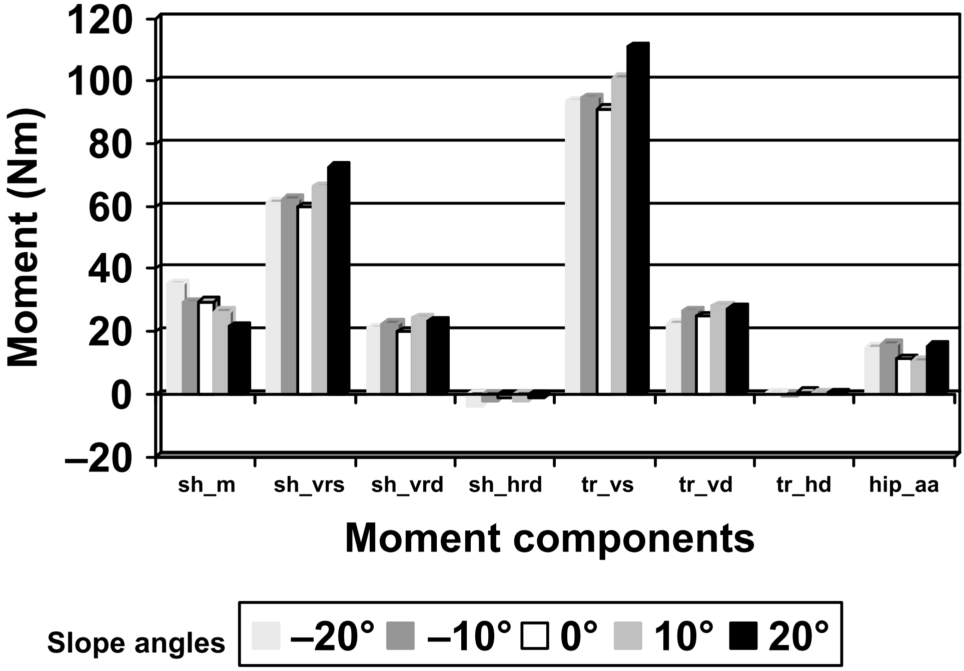

Figure 8. Component analysis of mean peak L5/S1 moments for the leg lift.

moments acting on/about the spine. It is reasoned that human performance plays an important role in this process in that at least some of the factors that impact these spinal loads are often within the control of the individual performing the lifting task. This indicates that the lifter's perception of muscular stress (Mirka *et al.*, 1998), whole-body stability and slip potential (Zhao *et al.*, 1987) (to name but a few potential factors) may impact the individual's kinematic lifting strategy. One might expect a lifter that has concerns about losing their balance during a lift to move more slowly, or to focus on keeping their dynamic centre of gravity more precisely over their base of support. The results of the present study indicate that body posture, body kinematics and peak L5/S1 moment did, in fact, vary as a function of lift technique and ground slope angle.

In this study the magnitude of the peak L5/S1 moment was significantly larger for inclined slopes than for flat and declined slopes in the freestyle and leg lifts. The more detailed component analysis showed consistent increases in both the moment created by the effect of gravity on the mass of the upper extremity and box and the moment created by the effect of gravity on the mass of the torso as slope angle changed from − 20° to 20°. This was confirmed by noting that the trunk flexion angle increased as slope angle increased from − 20° to 20°. There seem to be two factors that are creating this response. First, in the conditions where the work surface is inclined (toes higher than heels), a significant percentage of the available dorsiflexion range of motion of the ankle joint is consumed by simply standing upright on the inclined surface. As one attempts to lower the center of mass of the torso by flexing the knees (as when performing a leg lift or a freestyle lift), the end of the range of motion of the ankle joint is reached rather quickly. If one attempts to flex the knees further, the centre of mass of the torso must move posteriorly because the shank can no longer rotate anteriorly at the ankle. To compensate the torso must flex further forward to keep the dynamic centre of gravity over the base of support. If it does not, the person will fall over backwards. Given that during a back lift there is little knee flexion, this theory would support the finding of no effect of slope angle on L5/S1 moment.

The above description of the effect of ankle range of motion on the kinematics of lifting accounts for the changes in L5/S1 moment in the inclined conditions, but does not adequately account for these changes across the declined conditions. A second factor having to do with balance and minimization of required ankle plantar flexion moment is hypothesized. The results of the L5/S1 moment data show (and are confirmed by the trunk flexion data) that the lifter assumed a more upright posture as the degree of decline increased. The non-response to slope angle in the back lift condition indicates that, subject to the constraints as laid out by the experimenter (must perform a back lift), the lifter simply accomplished the lift by exerting high levels of plantar flexion moment with the gastrocnemius and soleus muscles (a stressful response compounded by the shortened length of these muscles due to the plantar flexed position of the ankle joint). However, given the opportunity in the knee and freestyle lifts, the lifter chose the less stressful approach of maintaining a more upright posture that keeps the stress in the plantar flexors to low levels.

The component analysis also revealed that in the freestyle lifting condition angular acceleration of the trunk was a strong factor in generating the overall response of the peak L5/S1 moment. The underlying biomechanics of this response can be hypothesized to be attributable to the changes in stability proposed by Opila *et al.* (1988) and Franklin *et al.* (1995) in the static case. The slower, more controlled trunk extensions during the lifts on the declined slope angles found in the current study would be consistent with a level of increased caution because of a perception of increased instability in these conditions. As the slope increased up to the maximum incline case, the ability of the plantarflexors to exert force increased and thereby allowed the individual to feel more confident in accelerating the mass of the trunk.

There are several limitations to the current study that should be considered and point to future research directions. The principal limitation of the current study is that the biomechanical model employed in this study only assessed the external moments acting about the L5/S1 joint. The trunk muscle forces that generate the necessary internal moments to produce the trunk motions are of critical importance for truly understanding the biomechanical loading on the spine. Due to their biomechanical disadvantage relative to these external loads, the trunk extensor musculature must produce extremely high forces during even simple static load holding tasks. During conditions of dynamic lifting on sloped ground surfaces that will likely decrease the stability of the lifting environment, it is likely that there will be an increase in the coactivation of the antagonist muscles (rectus abdominis, external obliques) thereby increasing the loading on the spine (both compression and shear loads) in an effort to maintain spinal stability. A study of the effects of lifting on sloped surfaces employing electromyography would prove invaluable to overcoming this limitation. Second, there are a number of simple methodological simplifications that were adopted to simplify the experimental protocol in this exploratory research. One of these simplifications is that the effects of slope angle and lifting technique were tested only with one load (10 kg). Schipplein *et al.* (1990) demonstrated that load magnitude influenced the sequence of joint activations with heavier weights tending to cause the knees to extend earlier during the lift than with lighter weights, suggesting a change in the strategy employed by the lifter. Testing the effects of varied lifting loads on this slope angle response could prove insightful. Another simplification was that the subjects performing these lifting tasks were fully aware of the task to be performed, as they performed these lifts in a repetitive lifting scenario. Some of the more interesting responses might be elicited when there is some uncertainty/unfamiliarity with the lifting task whereby stability might be further compromized and the kinematics and kinetics (and muscle coordination strategies as noted above) could be evaluated.

5. Conclusions

The main goal of the present study was to investigate the effect of ground slope angle and lifting technique on the L5/S1 joint moment and lifting kinematics during sagittally symmetric lifting tasks. The peak moment at the L5/S1 joint (computed by the two-dimensional dynamic biomechanical model) was affected by the ground slope surface during the freestyle and leg lift tasks. As slope angle increased from − 20° (declined) to 20° (inclined), peak moment at the L5/S1 joint increased. These results were found to have their origins in changes in the trunk flexion angles employed by the lifter. Lifting technique also had an effect on the peak L5/S1 moment, showing less peak L5/S1 moment in the leg lift than in the back and freestyle lifts. This effect included important changes in the angular acceleration of the torso. A biomechanical interpretation of these results indicates that the characteristics of the ankle joint (dorsiflexion range of motion and plantarflexion strength) are playing a critical role in dictating the lifting kinematics and kinetics of the torso as individuals perform lifting tasks on sloped surfaces.

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