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ABSTRACT

Leaning against a stationary barrier during manual materials handling tasks is observed in many industrial environments, but the effects of this kinematic constraint on low back mechanics are unknown. Thirteen participants performed two-handed lifting tasks using both a leaning posture and no leaning posture while trunk kinematics, muscle activity and ground reaction force were monitored. Results revealed that lifting with the leaning posture required significantly less activity in erector spinae (26% vs. 36% MVC) and latissimus dorsi (8% vs. 14% MVC), and less passive tissue moment compared with the no leaning posture. Peak sagittal accelerations were lower when leaning, but the leaning posture also had significantly higher slip potential as measured by required coefficient of friction (0.05 vs. 0.36). The results suggested that the leaning lifting strategy provides reduced low back stress, but does so at the cost of increased slip potential.

Keywords: manual materials handling; kinematic constraints; low back

1. Introduction

Industrial manual materials handling tasks often require lifting a load over a static barrier such as a railing or the side of a storage bin. The constraint that this barrier places on the kinematics of the lower extremities has a direct impact on the postures of the torso and it is believed that this will influence lifting biomechanics and lumbar stress. A review of the literature revealed that prior studies on this topic have focused on an alternative strategy wherein lifters used their off hand to support the weight of the upper body on the barrier while the dominant hand lifts the load (Ferguson et al., 2002; Kingma and van Dieën, 2004). Both studies illustrated the superiority of this strategy in terms of reduced trunk moment, reduced spine compression and reduced anterior-posterior shear force on low back. While this approach is shown to be effective at reducing spinal loads, this option is not available during two-handed lifts and so the uncertainty of the biomechanical effects of two-handed lifting over a barrier persists.

The two-handed lifting over a barrier are commonly observed in lifting task of crab fishermen in North Carolina wherein the LBP was shown as the highest cause of work impairment, holding 17.7% (Lipscomb et al., 2004). Mirka et al. (2005) evaluated biomechanical stresses placed on lumbar spine during the work activities of crab fishing by employing continuous assessment of back stress (CABS) methodology, which characterizes the stress on the low back throughout the workday, expressed in terms of time-weighted histograms (Mirka et al., 2000). The results of this study showed that the workers pulling the crab pots from the water or side of the boat up into the sorting table (using two hands) deserve attention in terms of a risk of LBP (Kucera and McDonald, In Review; Mirka et al., 2005). The crab pots used by fishermen in the estuary waters of North Carolina are big and heavy, 60cm × 60cm × 60cm cages made of chicken wire and framed with rebar, weighing between 3 and 12 kgf (depending on catch) and are lifted at a rate of one lift per minute. These pots are typically pulled up to the side of the boat by a mechanised “pot-puller” and then the fishermen reach over the side of the boat and lift the pot into the boat. A common lifting strategy observed in small-boat crab fishing operations is to lean against the side of the boat (washboard) with one or both thighs to handle big and heavy crab pots when lifting the crab pots from the water. If the fishermen choose not to lean against the washboard, hyper-flexion of trunk and/or asymmetric lifting are typically observed. If the fishermen choose to lean against the washboard, they are not able to use their legs to help with the lifting motion because the knee and ankle degrees of freedom in the kinematic chain have been lost. In addition, the horizontal external force provided by the interaction between the thighs and the washboard generates additional anterior-posterior ground reaction forces that can increase the slip potential on the slippery deck surface. However, from the opposite point of view, the leaning on a barrier could increase the stability of the entire body by providing additional contact points between body and stationary objects where the support provided by additional contact could reduce the rocking motion on the boat. These observations make the exploration of the biomechanics of these kinematically constrained leaning postures worthy of further exploration.

One previous study considered the effect of a shin-level kinematic constraint on low back biomechanics during lifting. Shu et al. (2007) evaluated the differences in activation levels of trunk extensor muscles while kneeling on a knee support (i.e. loss of the degree of freedom of the ankle joint). In this study the participants were asked to maintain a designated trunk flexion angle and then receive and hold a weight that was released into their hands by the experimenter. The kinematic constraint eliminated the motion of the ankle joint but allowed participation of the knee joint in supporting this load. Their results showed that the loss of the degree of freedom at the ankle joint had little effect on the activation level of latissimus dorsi and multifidus muscles during this task. While this previous study provided some information regarding the effect of a kinematic constraint, it was somewhat limited in that it only considered the constraint on the ankle joint – a joint with relatively limited direct impact on low back function. It was felt that limiting the participation of the knee joints through a kinematic constraint may be much more impactful on the function of the low back. The goal of current study was to investigate the effect of a thigh-level kinematic constraint by leaning against the barrier on trunk muscle activation and lifting kinematics.

2. Methods

2.1. Overview of the study design

The lower extremity kinematic constraint employed in this study was a thigh-level railing simulating a washboard on the side of a small fishing boat (Figure 1). This constraint led to the loss of two degrees of freedom in the kinematic chain (ankle and knee joints). There were two phases in this study: a static phase that involved static weight-holding tasks and a dynamic phase that involved free dynamic lifting tasks. The static trials were designed to understand how the muscles of the lumbar region function under leaning and no leaning conditions. The dynamic trials were designed to quantify the trunk kinematics and ground reaction force used to calculate the required coefficient of friction (RCOF) of the floor during the leaning and no leaning conditions.

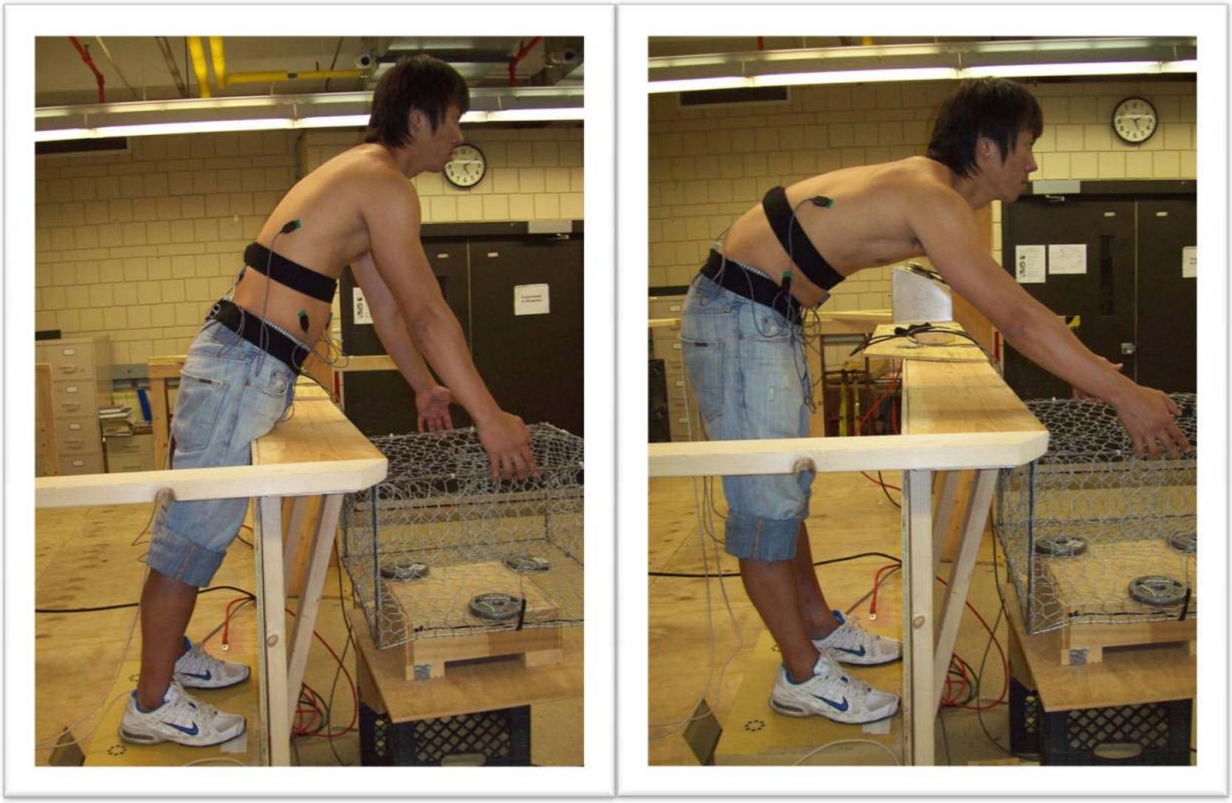

Figure 1. Experimental task: comparison of two lifting postures. Left: leaning, 70 cm height, Right: no leaning, 70 cm height.

2.2. Participants

Thirteen male participants were recruited from the university undergraduate and graduate student population of Iowa State University. They did not report any chronic problems or current pain in the low back or lower extremities. Each participant provided written informed consent prior to participation. The average and standard deviation of age, stature and whole body mass of participants were 28.1 yr (4.0), 172.5 cm (2.7), and 71.5 kg (7.2), respectively.

2.3. Experimental apparatus

The experimental setup was designed to simulate a boat with 82 cm height rail, which served as the lower extremity kinematic constraint during leaning conditions. The height of rail was selected based on measurements of boats in a field study of North Carolina crab fisherman. The load was a common 60 cm (L) × 60 cm (W) × 35 cm (H), 9 kg crab pot used by commercial crab fisherman.

2.4. Experimental equipment

During the static phase, surface electromyography was used to capture the activities of the ten sampled muscles (Model DE-2.1, Bagnoli™, Delsys, Boston, MA) (data collected at 1024 Hz), and a magnetic-based motion analysis system was used to capture the instantaneous lumbar curvature (The MotionMonitor™, Innovative Sports Training, Chicago, IL) (data collected at 102.4Hz).

During the dynamic phase, the lumbar motion monitor (LMM) (Chattanooga Group Inc., Chattanooga, TN) was used to capture the three-dimensional trunk kinematics (data collected at 60 Hz). A Bertec force platform (Bertec, Columbus, OH) was used to capture ground reaction forces (data collected at 60 Hz) used to calculate the RCOF.

2.5. Experimental Design

2.5.1. Independent variables

A 2 × 3 repeated measure design was employed that had two levels of posture (POSTURE: leaning, no leaning) and three levels of load height (HEIGHT; 85 cm, 70 cm and 55 cm from the ground level) which refer to the height of the hands as the participant grasped the crab pot. There was one replication of each of the six conditions in each phase resulting in twelve trials in both the static and dynamic phases of the experiment. All trials within each phase were completely randomized.

2.5.2. Dependent variables

In the static phase there were six dependent measures, and during the dynamic phase there were two dependent measures. Two types of extension moment generator including the active mechanism (muscle tissue) and the passive mechanism (ligaments, discs and fascia) were investigated in the static trials, because a pilot study revealed that the HEIGHT chosen in current study, specifically 55 cm and 70 cm, require over 60 degree trunk flexion where the passive tissues are in tension and begin to offset the external torque (i.e., initiation of flexion-relaxation phenomenon (FRP)) (Floyd and Silver, 1951 and 1955; Shin et al., 2004). To capture the active muscle activity, the average (across muscle pairs), normalized EMG included five bilateral muscles: erector spinae (ES), latissimus dorsi (LD), rectus abdominis (RA), external oblique (EO) and gastrocnemius (GAS). The extensor moment generated by the passive tissues low back was estimated using the technique of Dolan et al. (1994) (described in more detail in Section 2.7). In the dynamic phase of the experiment, the peak sagittal plane angular acceleration was found from the LMM data and the peak anterior-posterior and medio-lateral ground reaction forces were found using the force platform, used to calculate the RCOF. Both were captured during the concentric lifting motion.

2.6. Experimental procedures

Upon arrival the experimental procedure was described to the participant and informed consent was obtained. The participants then participated in a five minute warm-up session to prepare the muscles of the low back and lower extremity. The ten surface electrodes were secured on the skin over the selected muscles. The sampling locations for these muscles are as follows: (1) erector spinae: 3.5 cm from the vertebral midline at L2 level, (2) latissimus dorsi: most lateral portion of the muscle at the level of T9, (3) rectus abdominis: 5 cm above the umbilicus and 3 cm lateral to the midline, (4) external oblique: 10 cm from the midline of the abdomen and 4 cm above the ilium at an angle of 45° and (5) gastrocnemius: 2 cm medial from the midline of calf (location of largest muscle mass). The participant completed a series of isometric maximum voluntary contraction (MVC) exertions. For the erector spinae, rectus abdominis and external oblique muscles, a lumbar dynamometer was used to provide a static resistance at the 40 degree trunk flexion angle (Marras and Mirka, 1989). For the gastrocnemius muscles, participants were asked to rise on the balls of their feet against manual resistance on their shoulders provided by the experimenter. For latissimus dorsi, participants asked to bend their elbow to 90 degrees, abduct their shoulder to 90 degrees and maximally adduct against manual resistance provided by the experimenter. Two magnetic sensors were then secured on the skin on the midline of the spine - one at the L1 level and the other at the S1 level. The participants were then asked to stand in an upright posture and then to bend forward to a full trunk flexion posture to establish their full sagittal plane range of motion. As they performed this activity data from the magnetic motion sensors on L1 and S1 were captured. This was used to calibrate (express as % of range of motion) the lumbar motion data collected during the experimental trials.

Before beginning the experimental trials, verbal instructions were provided describing the leaning and no leaning postures. Participants were told that during the leaning condition they were to lean against the railing with both thighs and that they should not touch the railing during the no leaning condition (Figure 1). The participants were allowed to find the best lifting strategy in both the leaning and no leaning postures during practice. Also, the participants were asked to step on to the force platform and find a comfortable width of their feet after practice lifting at various heights. This location of their feet was marked and they were told to keep their feet in this position throughout the experimental trials. The trials in the static phase required that the participant flex the torso and grasp the load (9 kg crab pot) and lift it ~5 cm from its resting height and hold that posture for 5s while EMG and magnetic motion sensor data were collected.

Between trials, participants were given a rest period of 20 seconds. After completion of all trials, the electrodes and the magnetic sensors were removed.

The second phase began by securing the LMM to the back of the participant and they returned to their position on the force platform. During the lifting trials the participants began in an upright position, bent over to grasp the top of the load and come to an upright position, lifting the pot into the boat. During the trials, both LMM and force platform data were collected. Two trigger signals, one at the point when the participant first touched the crab pot and the other at the end of lifting motion (full upright posture), were also manually recorded by an experimenter in each trial to define the full flexion point and the upright posture, used for force platform data analysis. A rest period of 20 seconds was provided between trials. The LMM was removed and participant was free to leave.

2.7. Data processing

The unprocessed EMG data collected during static phase of the experiment were filtered (high-pass 10 Hz, low-pass 500 Hz and notch filtered at 60 Hz and 102.4 Hz and their aliases). For the MVC exertions, the filtered signals were full wave rectified and averaged into 1/8 second windows. The maximum 1/8 second window was indentified for each muscle group and was used as the denominator in order to normalize the EMG data during lifting tasks. For the EMG data collected during experimental trials, the filtered signals were full wave rectified and then averaged over the static weight holding time period. These values were used as the numerator in the normalization process. Finally, the normalized EMG of the right and left muscles of each bilateral pair were averaged.

The sagittal plane angles measured by magnetic sensors placed on L1 and S1 were used to calculate passive moment on low back during static trials. Lumber curvature (LC) was calculated for both the including upright standing and full flexion postures, and the static experimental trials using Equation 1. These values were then used to measure percentage of range of flexion using Equation 2. Finally, this percentage flexion value was used to calculate the passive tissue moment employing by Equation (3) (Dolan et al., 1994).

$$\text{Lumbar curvature (LC in deg)} = \text{Sagittal Angle}_{(L1)} - \text{Sagittal Angle}_{(S1)} \quad (1)$$

$$\text{Percentage Flexion (PF in \%)} = \frac{[LC - LC_{standing}]}{[LC_{fullflexion} - LC_{standing}]} \times 100 \quad (2)$$

$$\text{Passive tissue moment (in Nm)} = 7.97 \times 10^{-5} \times PF^3 + 12.9 \quad (3)$$

The forceplate data were used to calculate the required coefficient of friction (RCOF) which is employed to determine slip potential under a certain floor condition. The RCOF was determined in each dynamic trial as the ratio of peak of the vector sum of the horizontal forces (anterior-posterior (X) and medio-lateral (Y)) over peak vertical force (Z) (Hanson et al., 1999).

$$\text{Required coefficient of friction} = \frac{\sqrt{X^2 + Y^2}}{Z} \quad (4)$$

2.8. Statistical analysis

All statistical analyses in this study were conducted using SAS®. Prior to model analysis, diagnostic tests were performed on the data, including, test for homoscedasticity (Bartlett's Test and Levene's Test) and normality (Anderson-Darling Normality Test) (Montgomery, 2001). Dependent variables that violated one or more assumption were transformed so that the ANOVA assumptions were fully satisfied (Montgomery, 2001).

Due to the multivariate nature of the data collected in this study, both MANOVA and univariate ANOVA techniques were used. Multivariate analyses of variance (MANOVAs) were conducted on all response measures to control the experiment-wise error rate. Only those independent variables found to be significant in the MANOVA were pursued further in the univariate ANOVA. Post hoc tests employing Bonferroni's method were then performed on these significant main effects. A *p*-value less than 0.05 were regarded as the standard level of significance of an effect in current study.

3. Results

The results of MANOVA for average NEMG showed significant effects of POSTURE and HEIGHT, but there was no significant interaction effect between POSTURE and HEIGHT (See Table 1). Accordingly, the interaction effect was not considered in subsequent data analysis. Univariate ANOVAs were conducted on each of the five muscles and revealed a significant effect of POSTURE on all five selected muscle activities. The results showed that a leaning posture requires significantly lower muscle activation as compared to no leaning posture in the erector spinae, latissimus dorsi, rectus abdominis, external oblique and the gastrocnemius (Figure 2). However, the magnitude of difference in rectus abdominis (1.05%) and external oblique (0.64%) was quiet small, suggesting minimal or no significant effect in a biomechanical view point. The effect of HEIGHT was to have ~5 % reduction in gastrocnemius activity at the highest load position (85 cm) as compared to the others (55 and 70 cm).

Table 1. MANOVA and ANOVA results for average, normalized EMG.

Independent Variables	MANOVA (Wilks' lamdba)	ANOVA results				
		Dependent Variables				
		ES	LD	RA	EO	GAS
Posture	**$p < 0.0001$**	**$P < 0.0001$**	**$P < 0.0001$**	**$P < 0.0001$**	**$P < 0.0001$**	**$P < 0.0001$**
Height	**$p < 0.0001$**	$p = 0.2753$	$p = 0.5628$	**$p = 0.0003$**	$p = 0.6261$	**$p = 0.0002$**
Posture × Height	$p = 0.0673$	N/A	N/A	N/A	N/A	N/A

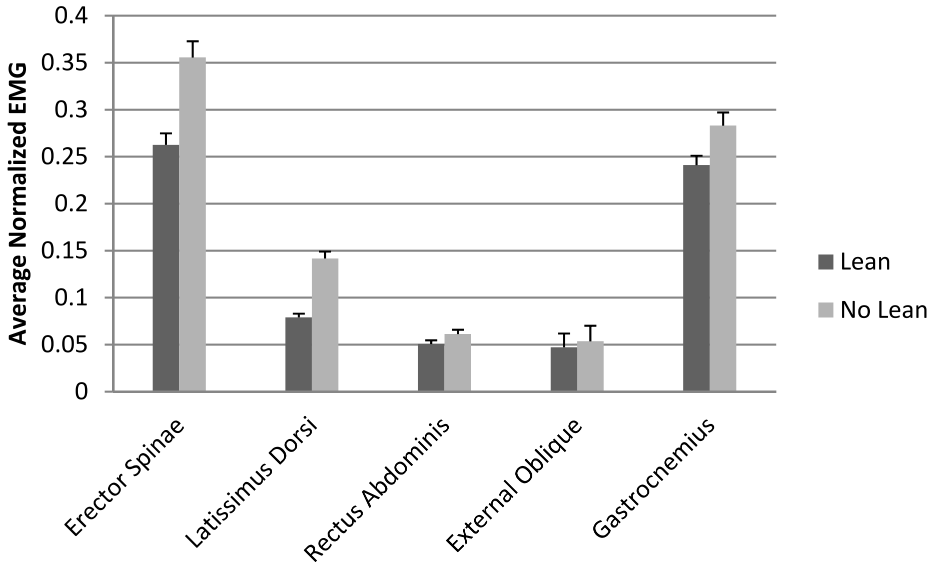

Figure 2. Effect of the POSTURE on NEMG. All differences are statistically significant. (Error bars show standard error.)

The results of the analysis of the passive tissue moment showed a significant effect of POSTURE ($p < 0.0001$), HEIGHT ($p < 0.0001$) and their interaction ($p = 0.0255$) (Figure 3). Simple effects analysis confirmed that both main effects were significant.

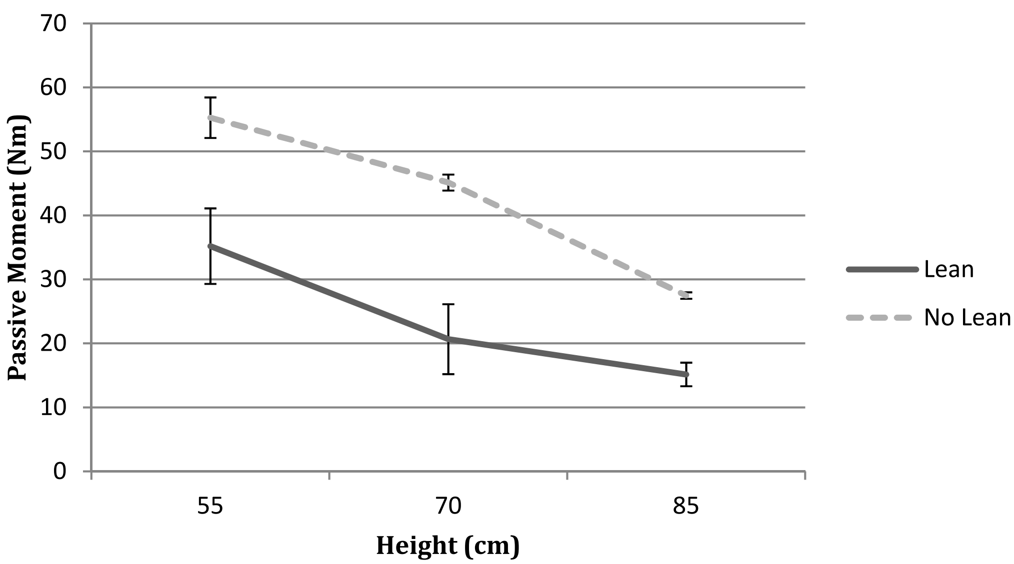

Figure 3. Interaction of POSTURE and HEIGHT on passive tissue moment. (Error bars show standard error.)

Regarding lifting kinematics, the result of ANOVA for angular acceleration in sagittal plane during a concentric lifting motion showed significant effects of POSTURE ($p < 0.0001$), HEIGHT ($p < 0.0001$) and its interaction ($p < 0.0001$) (Figure 4). Simple effects analysis, however, revealed that there is no difference between leaning and no leaning conditions at the height of 55 cm ($p < 0.4319$) when it was sliced by each HEIGHT (other two levels of HEIGHT showed significant effects of POSTURE ($p=0.0424$ (70 cm) and $p<0.0001$ (85 cm)). Also, the effect of HEIGHT was significant in both leaning and no leaning when it was sliced by POSTURE ($p<0.0001$) (Figure 5).

In regards to the RCOF, the results of ANOVA for RCOF also showed significant effects of POSUTRE ($p < 0.0001$), HEIGHT ($p = 0.0032$) and its interaction ($p = 0.0018$). Simple effects analysis revealed that HEIGHT was not significant in the no lean condition, but confirmed POSTURE as a significant main effect.

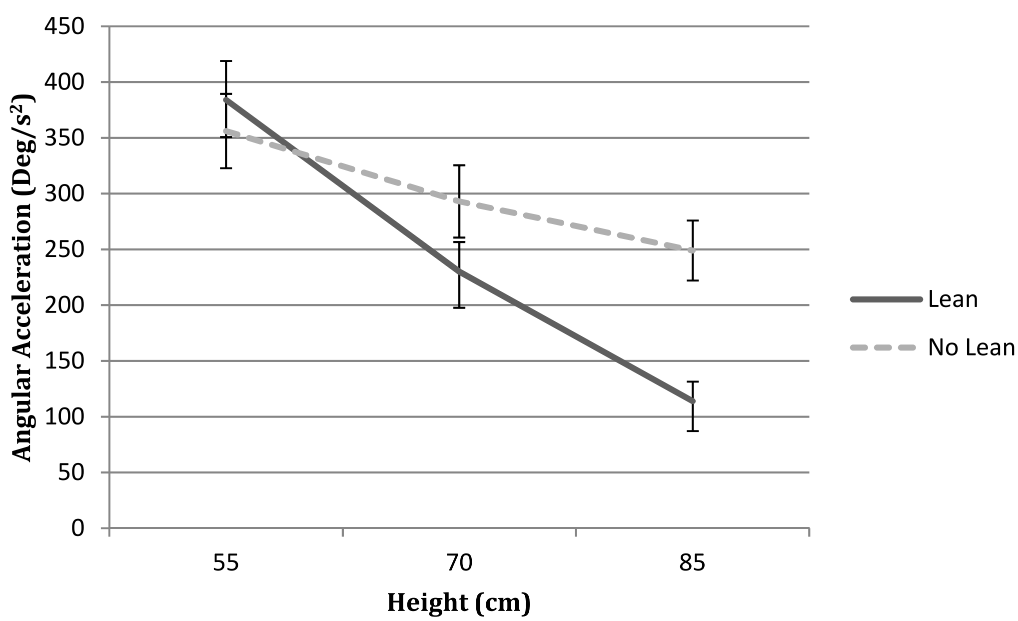

Figure 4. Interaction of POSTURE and HEIGHT on peak sagittal plane angular acceleration. (Error bars show standard error.)

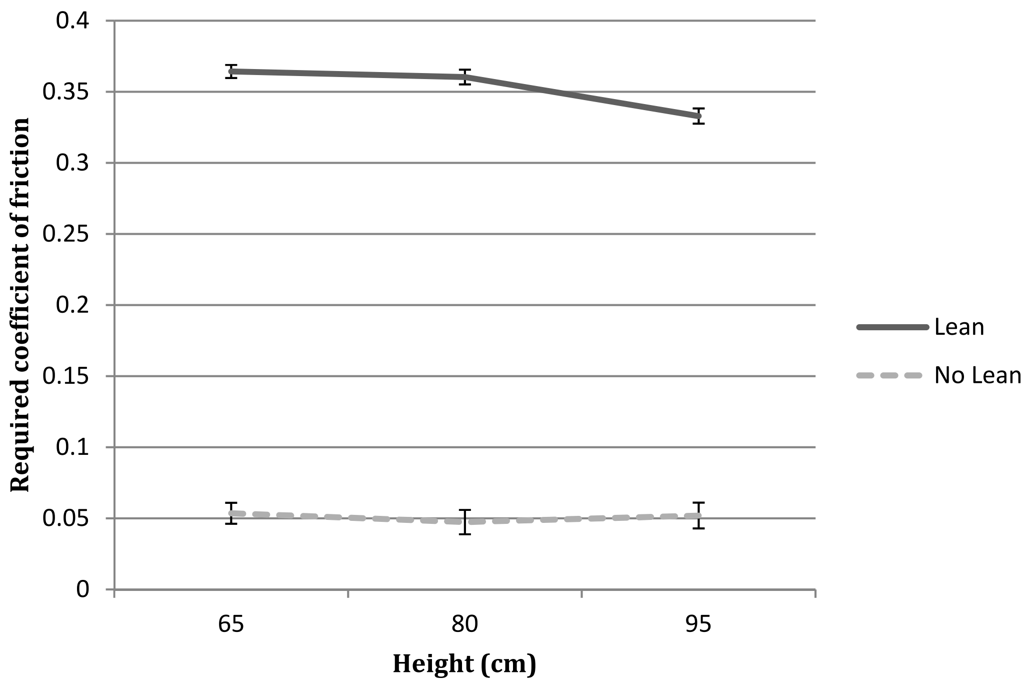

Figure 5. Interaction of POSTURE and HEIGHT on required coefficient of friction. (Error bars show standard error.)

4. Discussion

Understanding the impact of a leaning posture on low back biomechanics can provide valuable insight into possible ergonomic interventions for lifting in many scenarios. The particular scenario considered in the current study was lifting heavy loads from over the side of a small commercial fishing vessel. Quantifying the trunk kinematics through motion analysis, the muscle activation level through electromyography, and slip risk through required coefficient of friction can provide the type of quantitative data that will indicate whether this would be effective intervention in this particular work environment.

Normalized EMG results showed that the no leaning condition requires significantly greater trunk muscle activities (both agonist and antagonist) than did the leaning condition. The first thing that one notes in evaluating the postures assumed during these static contractions is that the leaning posture allows the pelvis to move anteriorly (Figure 1), thereby moving the fulcrum of the biomechanical system closer to the load and reducing the moment generated by the external load. This observation is consistent with the results of Kingma and van Dieën (2004) which showed a reduction in the distance between L5/S1 and external loads by supporting the upper body with the free hand during lifting. Second, the passive components of the low back also suggested the benefit of the leaning posture by showing that the moment generated by the passive tissues of the low back were greater under the no leaning condition. As the trunk flexion is deeper the passive tissues are in tension and begin to offset the external torque instead of the active tissues. Consequently, the active tissue captured by EMG shows no activity (i.e., FRP), and the passive tissue moment provides additional information predicting spinal loading. Considering that the passive mechanism initiated over 60 degree trunk flexion and enhanced with more trunk flexion, the participants tended to keep a more upright trunk posture during the leaning condition, instead of the hyper trunk flexion observed during the no leaning condition for reaching an object (Figure 1). In line with this, the lumbar flexion angle during the leaning condition was significantly smaller than that observed in the no leaning condition resulting in a lower passive tissue moment. With regard to low back loading, it is clear that the leaning posture is superior.

Less clear are the impacts of the leaning posture on lower extremity biomechanics and the resulting slip potential from this technique. The EMG results of gastrocnemius showed a significant (~15%) reduction suggesting a decrease in the necessary plantar flexion moment during the leaning condition as compared to the no leaning condition, indicating a positive effect of leaning. However, the nature of the leaning posture generated significantly higher RCOF than the no leaning condition. The nature of the leaning posture required that the participants push against the barrier with the thighs. With this pushing force comes an equal and opposite ground reaction force that could result in greater RCOF. In the current study the RCOF was shown to vary significantly as a function of load height during the leaning condition with the lower load heights generating the greater RCOF. While our laboratory simulation of the process of lifting the load from three different heights had high fidelity in some characteristics, the realistic working conditions (wet surface, oil and other particles) will reduce this coefficient of friction and may alter the strategies employed by workers performing this constrained lifting task. For the best results, the working condition with dried floor (solids) and wearing shoes (rubber) could be satisfactory because the coefficient of friction between solids and rubber is between 1 and 4 (RCOF in the leaning posture: 0.35). Also, regarding the coefficient of friction between rubbers (1.16) a rubber mat on the working place may lower the slip potential.

Regarding the trunk kinematics, the result also showed slower peak angular acceleration of the leaning posture in sagittal plane than no leaning posture during a concentric lifting motion, except at the lowest level of height (i.e., 65 cm). It is well known that increased trunk acceleration have a significant impact on spinal force and moment because of the increased inertial force and moment (Marras et al., 1993; Marras and Davis, 1998). On this basis, slower lifting acceleration may be another benefit of the leaning posture.

Expanding the results of the current study to a more general recommendation for broader industry applications should be done with care. It is clear that leaning against a solid barrier will move the lifter closer to the load and thereby reduce the external moment of the load. Caution should be taken, however, when considering the slip potential that this leaning posture generates. Our results indicate that the RCOF is significantly greater with the leaning posture and it is also increased as the load height decreased. The RCOF can be counteracted by providing high friction floor surface (e.g., rubber mat) or vertical stabilizers in the floor against which the lifters feet can push to accomplish the lift in a safe manner. Therefore as one considers the effectiveness of a leaning strategy to reduce low back injury risk, one should consider environmental factors when developing the leaning strategy as an effective ergonomic intervention strategy.

There are several limitations to the generalizability of the results of the current study. First, participants in this study were physically fit, male college students with relatively limited experience in manual materials handling tasks and no experience in crab pot lifting on the boat. Previous studies found that inexperienced subjects generally demonstrated greater spinal loading than experienced manual material handlers when the moment exposure was the same (Marras et al., 2006). Future study with experts in crab pot lifting could result in different low back biomechanical responses. Second, the current study controlled variables such as lifting technique (two hand, symmetric lifting), load size and load weight and these variables might influence the strategy and the biomechanical response of the lifters under the leaning and no leaning conditions. Future research should provide insight into the interaction between these factors and the POSTURE.

5. Conclusions

This study considered the effects of a leaning posture on spine biomechanics and lower extremity slip potential. Our results showed that the leaning lifting strategy provides some biomechanical benefits over the no leaning lifting strategy (lower muscle activations levels, more controlled lifting motions, reduced passive tissue forces) but at a cost of increased required coefficient of friction. In some work environments where the coefficient of friction between the lifter and the floor is high this may not be an issues, however in the commercial fishing industry, the low coefficient of friction deck surface highlights the leaning posture as problematic.

Acknowledgements

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