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ABSTRACT

The objective of this study was to quantify the effects of ground surface motion on the biomechanical responses of a person performing a lifting task. A boat motion simulator (BMS) was built to provide a sinusoidal ground motion (simultaneous vertical linear translation and a roll angular displacement) that simulates the deck motion on a small fishing boat. Sixteen participants performed lifting, lowering and static holding tasks under conditions of two levels of mass (5 and 10kg) and five ground moving conditions. Each ground moving condition was specified by its ground angular displacement and instantaneous vertical acceleration: A): $+6^o$, $-0.54\ m/s^2$; B): $+3^o$, $-0.27\ m/s^2$; C): 0^o , $0 m/s^2$; D): -3^o , $0.27\ m/s^2$; and E): -6^o , $0.54\ m/s^2$. As they performed these tasks, trunk kinematics were captured using the lumbar motion monitor and trunk muscle activities were evaluated through surface electromyography. The results showed that peak sagittal plane angular acceleration was significantly higher in Condition A than in Conditions C, D and E ($698 deg/s^2$ vs. $612\text{-}617 deg/s^2$) while peak sagittal plane angular deceleration during lowering was significantly higher in moving conditions (conditions A and E) than in the stationary condition C ($538\text{-}542 deg/s^2$ vs. $487 deg/s^2$). The EMG results indicate that the boat motions tend to amplify the effects of the slant of the lifting surface and the external oblique musculature plays an important role in stabilizing the torso during these dynamic lifting tasks.

Keywords: lifting biomechanics; ground motion; fishing industry

1. Introduction

On-ship manual materials handling tasks have been shown to be associated with high prevalence of musculoskeletal problems in the fishing industry (Driscol et al., 1994; Thomas et al., 2001; Conway et al., 2002; Roberts, 2004; Jensen, 2000; Norrish and Cryer, 1990; Torner et al., 1988; Lipscomb et al, 2004). Heavy manual material handling is a normal task fishermen perform on ship (Kucera et al. 2008) and was reported by the fishermen as a main reason for high workload (Torner et al., 1988). Torner et al. (1988) reported a one-year prevalence rate of 70% for musculoskeletal problems among fishermen in Sweden, and Lipscomb et al. (2004) reported a one-year prevalence rate of 83.3% for musculoskeletal symptoms in North Carolina fishermen in the United States.

Working in a moving environment (e.g. on a ship) can create multiple problems for workers, such as motion sickness, loss of balance, physical fatigue and reduction of performance (Wertheim, 1998). Among these problems, balance problems and physical fatigue can be related with on ship manual materials handling work. Wertheim et al. (2002) evaluated maximum oxygen consumption and maximum power while the participant performed a graded exercise test on a cycle ergometer under stable conditions and those that would be experienced in three, dynamic ground motion conditions (on a small coast guard boat, random 3-D angular motions and on a ship on the open sea). These authors found a 6-10% reduction of maximum oxygen consumption when participants were working under a moving environment but failed to provide an underlying theoretical mechanism to explain these results. In an earlier study, these same authors showed that the oxygen consumption of a particular task increased by about 16% under a moving surface environment. These results may indicate that when performing physical tasks under moving environment one may reach to the same fatigue level much quicker than under stationary environment.

A number of studies have been conducted to quantify the effects of ship motion on the biomechanical responses during on-ship manual material handling tasks. Torner et al. (1994) investigated the effect of ship motion on low back loading during lifting. In that study researchers had one participant perform standing, holding and repetitive lifting at the motion center of a trawler (length 24 m, gross weight 164 ton with motion period approximately 8 s). They used a two-dimensional biomechanical model to calculate joint moment and L4/L5 level spine compression force during lifting. Their results showed that these ship motions can increase spine compression by up to 40%. In another study of effects of ship acceleration on low back stress, Kingma et al. (2003) performed a simulation study that mathematically superimposed ship motion data (gathered from two locations on a 120m frigate under two sea-state conditions) to a dataset of lifting and pulling kinematics data that were collected under stationary conditions. Their simulation results suggested that unfavorable timing of lifting can cause a moderate (up to 15%) increase in low back moments. The validity of this approach remains untested.

A follow up on-ship investigation by Faber et al. (2008) supported some of the conclusions reported by Kingma et al. (2003). Faber et al. (2008) investigated the effect of ship motion on spinal moments and compression forces during lifting under different motion conditions on a military vessel (42 m long and 9 m wide, motion period was about five seconds). They also compared the effect of free pace lifting and constrained pace lifting on spinal loading. Results from that study suggested that vertical acceleration of the ground surface increased net moment by 10.1% per m/s^2 of average absolute value of z-acceleration, and this acceleration has a greater impact than other directions of linear accelerations. They also showed that free pace lifting did not reduce the low back loading compared to the constrained pace lifting.

There are several studies that have investigated the effect of ground angular motion during lifting (Matthews et al., 2007 and Holmes et al., 2008). Matthews et al. (2007) investigated the effect of three ground angular motion conditions (roll, quartering, and pitch) on trunk kinetic and kinematics during lifting. In this study the ground motion was provided by an in-lab boat motion simulator executing an angular motion profile derived from a 45 ft long vessel experiencing 7 m waves with 5-10 s periods, and these responses were compared with those in a no-motion condition. Their results showed a significant decrease (~30%) in maximal trunk extension velocity under the roll (rotation about the anterior posterior axis) ground moving conditions as compared to the no-motion environment. Pitch motion (rotation about medial-lateral axis) was found to be the most difficult condition to maintain stability.

The rolling motion of a boat (i.e. rotation about the anterior–posterior axis) generates lower extremity postures and orientations similar to the postures seen in a study of slanted ground surfaces considered in Jiang et al. (2005). In this study, the authors investigated the effect of laterally slanted ground on back extensor muscle activities during static weight holding tasks. Four slanted ground angles (0^o, 10^o, 20^o and 30^o) were tested in that study and their results showed that both the right and left erector spinae showed increased activity with increased slant angle, with the contralateral muscle showing a more rapid increase in activity with greater slant angles. In this study, significant changes of muscle activation happened only in relatively large slanted angles (20^o and 30^o). The instability created with these slant angles resulted in higher levels of co-contraction, presumably to increase the safety of the lifting task.

While there have been a number of studies that have attempted to address the relationship between deck motions and biomechanical responses during lifting on a ship, these studies typically have considered the ship motions experienced by large vessels on the high seas. The effects of the ground motions that workers on a smaller boat experience in shallow water remain largely unknown. This is important because sea surface motion varies significantly between the sea surface far from shore and that experienced close to shore. When waves approach the shore the reduced water depth causes the wave steepness to increase (Trujillo and Thurman, 2008). Also large ships with more mass will experience a longer period of motion than smaller fishing boat due to their difference in total mass and inherent natural frequency. Most of the fishermen in the crab fishing and the gill net fishing industries work on relatively small fishing boat close to shore. Both the size of their boats and their proximity to shore make the application of the results from the research on deep sea vessels difficult to interpret relative to these smaller fishing vessels.

The purpose of current study was to quantify the effects of amplitude of sinusoid wave motion that would be typical of small craft motions (generating both vertical accelerations and angular displacements of the deck surface) on trunk muscle activation and trunk kinematics during lifting, lowering and weight holding tasks. This research was conducted on a boat motion simulator (BMS) which simulates the motion of a smaller sized boat fishermen use in the crab and gill net fishing industries.

2. Methods

2.1. Participants

Sixteen participants with average age 25 years (SD 3.6), stature 179 cm (SD 6.1) and total body mass 70 kg (SD 7.5) were recruited from the student population of Iowa State University and provided written informed consent before participation. All participants were free from any chronic and current low back pain and were told not to participate if they had "difficulties in maintaining body control during standing and walking". This screening criterion was put in place to screen for potential participants with balance disorders.

2.2. Experimental Apparatus

A boat motion simulator (floor surface 3.7 m long × 1.8 m wide) was built to provide a controlled moving environment for the participant to perform lifting tasks (Figure 1). The simulator has the ability to rock from side to side by manpower and provides a sinusoidal vertical and angular movement of the BMS which simulates the deck motion on a small fishing boat. The BMS moves with a natural period of 1.6 seconds. Two plastic crates (33 cm×33 cm×28 cm) with total mass of 5kg and 10kg were the loads to be lifted in this experiment. The crate had good handles and the height of handles was approximately 25 cm.

Insert Figure 1 about here

2.3. Data Collection Apparatus

Surface electromyography (EMG) was used to capture muscle activity levels. Six bi-polar electrodes (Model DE-2.1, Bagnoli™ Delsys) were attached to the skin over the bilateral muscle groups: erector spinae, rectus abdominis, and external oblique and these data were collected at 1024 Hz. The Lumber Motion Monitor (LMM) (Chattanooga Group Inc., TN) was attached along the back of the participant to capture the trunk kinematic (Marras et al. 1992). The LMM provided 60 Hz continuous measurement of angular position, velocity and acceleration in three cardinal planes of motion: sagittal, coronal and transverse plane.

2.4. Independent Variables

Two independent variables were considered in this experiment: MASS and CONDITION. MASS was the total mass of the load being lifted and had two levels: 5 kg and 10 kg. CONDITION referred to the ground condition (i.e. the instantaneous angular orientation and the instantaneous linear vertical acceleration) and had five levels: A): 6°, -0.54 m/s^2; B): 3°, -0.27 m/s^2; C): 0°, 0 m/s^2; D): -3°, 0.27 m/s^2 and E): -6°, 0.54 m/s^2 where condition A and B represent conditions where the ground surface is at the top of the range of motion and conditions D and E represent conditions where the ground surface is a the bottom of the range of motion (Figure 1.) The vertical acceleration profile of the BMS motion can be simplified as a simple harmonic motion and the instantaneous vertical acceleration can be calculated by using Equation 1. A and T represent motion amplitude and period respectively, and this equation is used to calculate the instantaneous dynamic acceleration rate starting from the peak of BMS motion. More specifically conditions A and E were when the BMS moved with a 4 cm amplitude and 1.6 second period (the natural period of the BMS) and the accelerations at either the peak or the trough of the motion were -0.54 m/s^2 and 0.54 m/s^2, respectively. Conditions B and D were similar to A and E but with a 2cm amplitude (-0.27 m/s^2, 0.27 m/s^2). In condition C the BMS was static so acceleration was 0 m/s^2.

$$Acc(t) = -A \times (2\pi / T)^2 \times \cos(2\pi t / T) \qquad \text{[Eq. 1]}$$

2.5. Dependent Variables

For the dynamic lifting tasks, four trunk kinematic variables were considered. Both peak sagittal angle (greatest trunk flexion) during the concentric lifting motion and peak sagittal angle (also greatest trunk flexion) during the eccentric lowering motion provided postural response information. Peak sagittal plane angular acceleration during the lifting motion and peak sagittal plane angular deceleration during the lowering motion provided important insight into the motion strategies employed by the participant. For the static weight-holding tasks, the normalized (to maximum) EMG response from the six bilateral muscles (Right Erector Spinae (RES), Left Erector Spinae (LES), Right Rectus Abdominis (RRA), Left Rectus Abdominis (LRA), Right External Oblique (REO) and Left External Oblique (LEO)) were the dependent variables. It must be clarified that "dynamic lifting tasks" and "static weight-holding tasks" refer to the motion required of the participant, not the motion of the boat. (i.e. the participant performed the static weight-holding tasks both when the BMS was moving and when it was stationary and the participant performed the dynamic lifting tasks both when the BMS was stationary and when it was moving.)

2.6. Experimental procedure

Upon arrival the participant was provided a brief introduction to the experiment and then written informed consent was obtained. The participant was guided through a five minute warm-up routine to stretch and prepare the muscles of the low back, upper and lower extremities, then fitted with six bi-polar surface EMG electrodes on the skin over three bilateral muscle groups (erector spinae, rectus abdominal and external oblique). A series of maximum voluntary contractions (MVC) were performed by using the static resistance provided by an isokinetic dynamometer (Mirka and Marras, 1993). MVC EMG signals for the trunk extensor (erector spinae) and flexors (rectus abdominis and external oblique) were captured by having the participant assume a sagittal symmetric, ~30° forward flexion trunk angle and perform extension or flexion task respectively against the dynamometer resistance. After these MVC trials, the LMM was secured to the low back of the participant.

The participant then moved to the BMS where he was asked to center himself on a fixed location on the deck of the BMS, 50 cm away from the midline of the deck. The participant was always facing toward the bow of the BMS with his feet width set at 120% of his shoulder width (this is a location and orientation of manual materials handlers often seen on small fishing boats.) The crate was set on the deck 50 cm from the midline of the boat.

In the experimental trials, the participant was asked to perform three repetitions of each load lifting and load lowering task in 30 seconds. For individual trials, the BMS moved at the designated amplitude (0cm, 2cm or 4cm) to create different lifting conditions (Figure 1.) The lifting task required the participant to first stand in a neutral upright posture on the deck of BMS, bend over grasp the load and lift it up to the upright standing posture. The lowering task was performed following each lifting task and the participant started from the ending posture of lifting task, bent over, lowered the load down to the deck, released the load and came back to upright posture again. The starting time of every lifting and lowering task was cued by experimenter by saying “Go”. The timing of this “Go” command was such that the lifter was performing the task at the designated position (peak or trough of the boat motion). Given the critical importance of the lifting/lowering motion occurring at just the right instant within the context of the overall boat motion, some training between the lifter and the experimenter was necessary so that when the experimenter said “Go” this produced the lifting/lowering motion in the correct time interval for achieving the designated experimental condition. After completing the three repetitions of the load lifting and lowering tasks, participant then performed a static weight-holding task (boat continued moving at the designated amplitude.) This task required the participant to hold the load with the handles at mid-thigh level for six seconds. This mid-thigh load height was chosen so that the participant had to flex torso to activate the erector spinae muscles, but avoid the effect of flexion relaxation that would come with more severe trunk flexion angle. During data collection, an event marker was pressed each time the boat reached the trough position and this provided useful information regarding boat motion that was used during data processing to help identify lifts occurring outside of the designated motion windows.

The combination of two levels of MASS and five levels of CONDITION resulted in ten different lifting scenarios. Two repetitions for each of the ten scenarios were performed, resulting in 20 lifting trials. The order of presentation of the experimental conditions was completely randomized.

2.7. Data Processing

The event marker data were used as the time for each trough point of the BMS motion, and the midpoint between two successive troughs was identified as the peak of the boat motion. For the dynamic lifting and lowering tasks, the timing of when the experimenter said "Go" and when the lifting/lowering task was performed was not always perfect. Therefore it was necessary to perform a data quality screening test on each lift. The technique employed was to use the LMM data to identify when the peak trunk extension acceleration occurred during the lifting task (or the peak sagittal deceleration during the lowering task) and evaluate the timing of this peak relative to the ideal peak (or trough) from the event marker data. If the peak sagittal acceleration (or deceleration) occurred within ±0.25 seconds (see Figure 1) of this ideal value, the trial was considered a success, if not, the lift was discarded. In a given trial, those lifting motions that were found to have occurred during the ±0.25 second window were averaged to create the dependent variables describing the trunk kinematics. The same ±0.25 second time interval was also used in the EMG data processing collected from static holding tasks. Data points within ±0.25 seconds of the time of the designated peak or trough were processed as described below.

The unprocessed EMG data were band-pass filtered at a low-pass frequency of 500 Hz and a high-pass frequency of 10 Hz. A notch filter was also applied that eliminated 60 Hz and its aliases and then these filtered signals were full-wave-rectified. The EMG signals from the MVC trials were reduced to 1/8th second windows and the maximum of these 1/8th second windows was the value used as the denominator in order to normalize the EMG data from the experimental trials. The EMG data collected in the ±0.25 second window were averaged and were used as the numerator for the calculation of the average normalized EMG.

2.8. Data Analysis

All statistical analyses in this study were conducted using Minitab 15. Prior to formal statistical analysis, the assumptions of the ANOVA procedure (normality of residuals assumption, non-correlation of residuals (i.e. independence) assumption, and constant variance of residuals assumption) were tested (Montgomery 2005, pp.76-79). Dependent variables that violated one or more assumptions were mathematically transformed using the log function so that the ANOVA assumptions were no longer violated (Montgomery 2005, p.80). Multivariate analyses of variance (MANOVAs) were then 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. Tukey-Kramer post-hoc tests were then performed on the significant main effects to further explore the nature of these significant effects. A criteria p-value of 0.05 was used in all statistical tests.

3. Results

EMG results from load holding task showed that both MASS and CONDITION had a significant effect on muscle activities, but the interaction effect was not significant (Table 1). Post hoc tests showed that higher levels of load mass generated higher muscle activity in all muscles groups, however the effect of CONDITION followed different trends for different muscles. From Figure 2 it can be observed that for the erector spinae muscle group, the left and right muscle showed different trends as a function of condition. While the vertical acceleration (and thereby the net sagittal plane moment for both muscles) changed at a constant rate in going from Condition A to Condition E the changes in the slant angle of the deck surface altered which of the erector spinae muscle would be considered the contralateral and ipsilateral muscle group. The result that these responses are not mirror images of each other indicates that there is an interaction between the magnitude of the vertical acceleration and the deck surface slant angle. In terms of the antagonist muscle groups, the RRA and LRA did not show any clear pattern among different conditions with relatively low activation levels. The external oblique muscles, however, showed a more consistent trend, with significantly higher muscle activity in the moving conditions (A and E) compared with stationary condition C, indicating a trunk stabilization role under these dynamic conditions.

Insert Table 1 and Figure 2 about here

The MANOVA and ANOVA results of trunk kinematics variables data from load lifting and lowering tasks are shown in Table 2. Consistent with the EMG results, trunk kinematics data revealed significant effect of MASS and CONDITION, while their interaction was not significant. The maximum sagittal acceleration during the lifting task and the maximum sagittal deceleration in the lowering task were significantly decreased with the increased load mass. CONDITION also had a significant effect on both acceleration and deceleration. As shown in Figure 3, maximum lifting sagittal acceleration in Condition A (when the load would feel lightest) was significantly higher than Conditions C, D and E. Figure 4 shows that maximum sagittal deceleration (eccentric) during the lowering task followed a different trend as compared to the response during concentric acceleration. In conditions A and E (-0.54 m/s^2 and 0.54 m/s^2) participants had similar deceleration values and they were significantly higher than the stationary condition C.

Insert Table 2, Figure 3 and Figure 4 about here

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4. Discussion

The activity levels of the bilateral erector spinae muscles followed unexpected trends that were the result of a complex interaction between the ground surface slant angle and the vertical acceleration. This created a situation where the role of contralateral and ipsilateral muscles was constantly changing. If one was to view a snapshot of this weight-holding task it would appear to be a sagittally symmetric task. However, the combination of the angular displacement at the feet and the vertical acceleration of the load and the trunk mass create medio-laterally directed forces that essentially change this to an asymmetric lifting task thereby creating the need for contra and ipsilateral muscle forces. Jiang et al. (2005) reported a significant increase of erector spinae muscle activity at 20^{o} and 30^{o} slanted ground angle (but not 10^{o}) and the contralateral muscle activity increased at a greater rate as compared to the ipsilateral muscle. In the current study, although the ground angle was much smaller (0^{o}, 3^{o} and 6^{o}) the significant effect of CONDITION would indicate that effect of slanted ground angle was magnified by the participants in order to maintain stability under the dynamic lifting conditions.

From the profile of RES and LES in Figure 2, the effect of both angular displacement and vertical acceleration can be clearly observed. In the stationary condition (Condition C), both RES and LES had very similar levels of muscle activity (21.1% and 21.2% respectively). Neglecting the effects of the dynamics (i.e. simply considering the changes in the slope of the deck surface) we would expect to see a mirror image response of these two muscles as a function of slant angle (RES muscle activity in Condition A would have the same muscle activation level with LES in Condition E, etc.) Therefore, the average of the two contralateral muscles (and ipsilateral muscles) in these mirror image conditions can be found and we describe this as “ideal” (Figure 5) and suggest that this is the pure effect of the slant angle of the deck surface. From Figure 5 the effect of acceleration on erector spinae muscle activity can be identified as the muscle activity difference between RES, LES and the “ideal” bars. Comparing the “ideal” situation for the contralateral muscle under conditions A and B

(-0.54m/s^2 and -0.27m/s^2 ground acceleration) reduced low back muscular activity by 3.0% and 2.7% respectively. When working as ipsilateral muscle the same acceleration reduced 3.7% and 3.3% of muscle activity.

Insert Figure 5 about here

Under the variable dynamic lifting conditions of this experiment, one would have expected significant effects of the magnitude of the acceleration and slant angle of deck surface on the levels of antagonist co-contraction. The results showed that the rectus abdominis muscles were largely unaffected by these changes, but the external oblique muscles followed a much more consistent trend indicating an important role in system stabilization. The significant medio-lateral component of the line of action of the external obliques would provide the necessary stabilization forces to counter the side to side forces as implied by the contralateral-ipsilateral shifting as observed in the erector spinae. The relatively simple, static exertions performed in this experiment might underestimate the level of external oblique muscle activity that would be required under more realistic, dynamic lifting motions performed on a fishing boat.

Kinematics data revealed that both MASS and CONDITION had significant effect on the maximum sagittal acceleration during lifting task, lighter mass caused higher sagittal acceleration rate. The effect of CONDITION could also be related to changes in the *effective* weight of the load. In Condition A, the -0.54m/s^2 vertical acceleration makes the load about 5% lighter than the static condition (Condition C) and 10% lighter that than Condition E. As expected, this “lighter” load generated the highest peak sagittal angular acceleration during the concentric lifting motion, but the opposite was not true – the peak sagittal angular acceleration in Condition E was not significantly lower than Conditions B, C or D. The results of this study confirm the concern of Kingma et al. (2003) that their simulation may make simplifying assumptions that could be false. The magnitude of the ground accelerations (and the accompanying angular displacements) in the current study did generate changes in the peak sagittal plane angular acceleration and decelerations used by the participants, but did not impact the sagittal plane range of motion.

In previous related studies researchers investigated the effects of sea motion on relatively large vessels where periods of motion are relatively longer than those experienced in smaller fishing boats. In Matthews et al. (2007) for example, the ship motion simulator employed in this study simulated a coast guard supply vessel experiencing 7 meter waves with 5-10 second wave period. Comparison of the results of this previous study with the current study is somewhat difficult for these reasons, but also because the current study placed fairly stringent controls on the magnitude of the instantaneous deck surface angle and vertical acceleration. In the Matthews et al. (2007) study, the boat simulator moved with a 5-10 second period and the participant lifted at a rate of six lifts per minute but the timing of the individual lifts was not controlled relative to the boat motions so the instantaneous angle and acceleration of the deck surface were not controlled and reported. The Matthews et al. (2007) approach may provide a more realistic view of lifting activities on a boat where the timing of the lifts is generally not controlled, but it also increases the variability in the biomechanical responses. The current study controlled the timing of the lifts relative to the boat motions via experimenter cues to lift, so that the effects of specific levels of deck motion characteristics could be related directly to the resulting biomechanics responses. While this may be interpreted as a limitation of the current study, it also allows for this more direct, quantitative evaluation of the effects of the dynamics of the boat motion of the relevant kinematic and muscle coactivation responses.

There are several limitations to the current work that should also be noted. First, the current study was conducted on an experimental set up that simulated a simple sinusoidal motion of a small fishing boat. More realistic motions of a small fishing boat are not always predictable and generally not purely sinusoidal. Also, the physical dimensions of the BMS in this study provided only one natural motion period (~1.6s). For safety reasons the amplitude of angular displacement of the ground motion never went beyond 6^{o} which represents only moderate sea conditions, more severe and unpredictable motions may provide interesting changes in the trunk kinematics and muscle coactivation patterns. Second, the participants in this study were college aged students with limited experience working on fishing boats. The responses of seasoned fishermen that have their "sea legs" would provide an interesting contrast for our results. Third, the current study only considered the vertical acceleration and coronal plane angular displacement during rolling motion, future research needs to be done to evaluate the effect of other type of ground motions (e.g. pitch and quartering). Finally, a laboratory study can provide good control of all independent variables and precise measurement of dependent measures, but a field study conducted on smaller fishing boat would provide valuable verification of the results of this study.

5. Conclusion

The purpose of this study was to investigate the effect of ground surface motion on kinetics and kinematics during manual material handling tasks. Normalized EMG results clearly showed the impact of both ground angular displacement and vertical linear acceleration on the trunk muscles. With a relatively small range of angular displacement used in this study, the erector spinae muscles experienced higher muscle activity when working as a contralateral muscle and this contralateral designation changed as a function of ground surface slant angle. External oblique muscle activity increased with the increasing ground motion indicating their role as an important stabilizer during this dynamic activity. Kinematics data showed that there were changes in the lifting strategy with greater angular acceleration under conditions where the vertical acceleration of the ground surface made the load feel lighter than under the other motion conditions.

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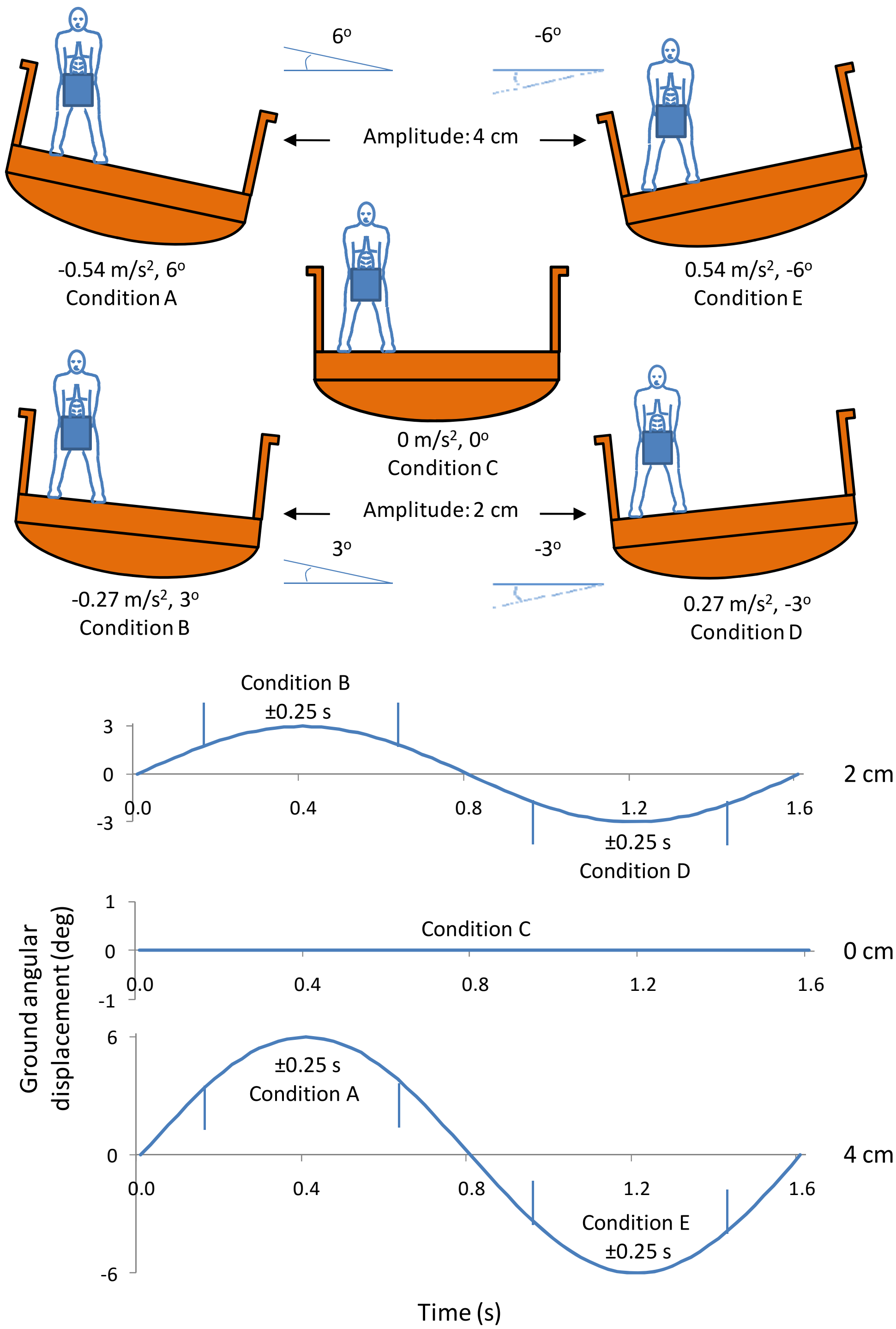

Figure 1: Coronal plane (front) view of the experimental set up and demonstration of the five ground surface conditions.

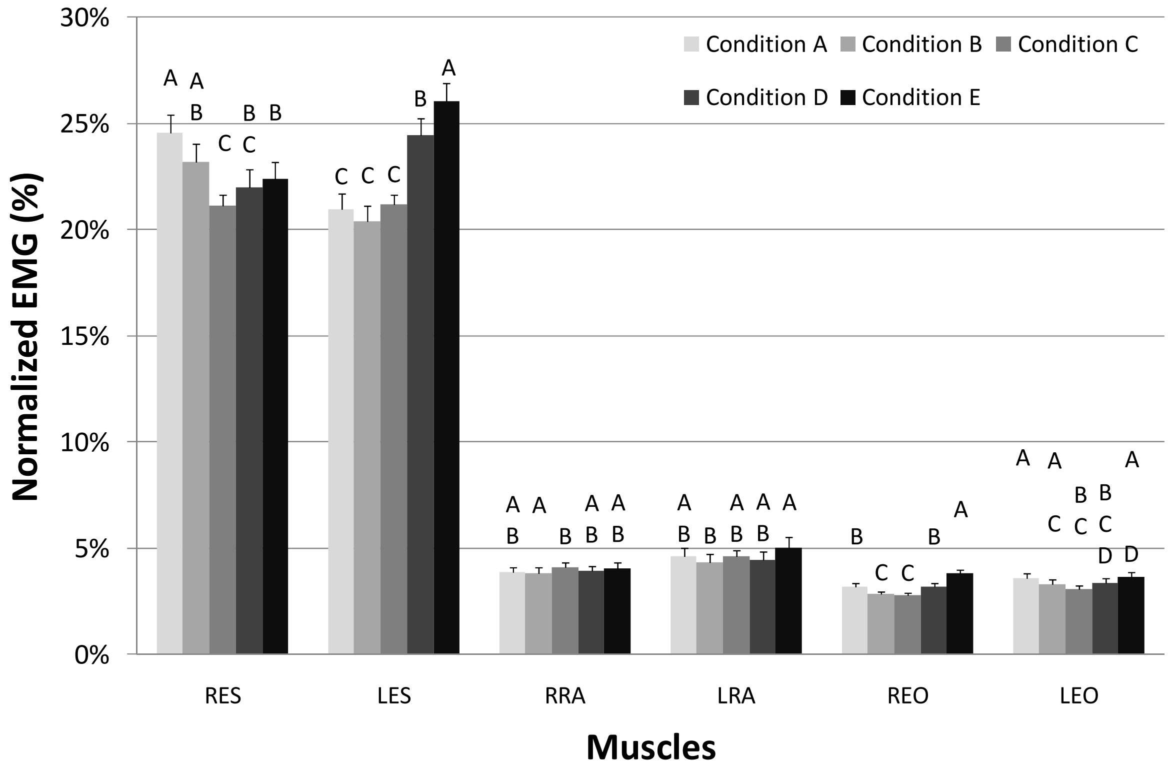

Figure 2: Effect of CONDITION on muscle activity during load holding task. The letters above each column are from the Tukey-Kramer post hoc test. Different letters represent muscle activity levels that are statistically different from one another.

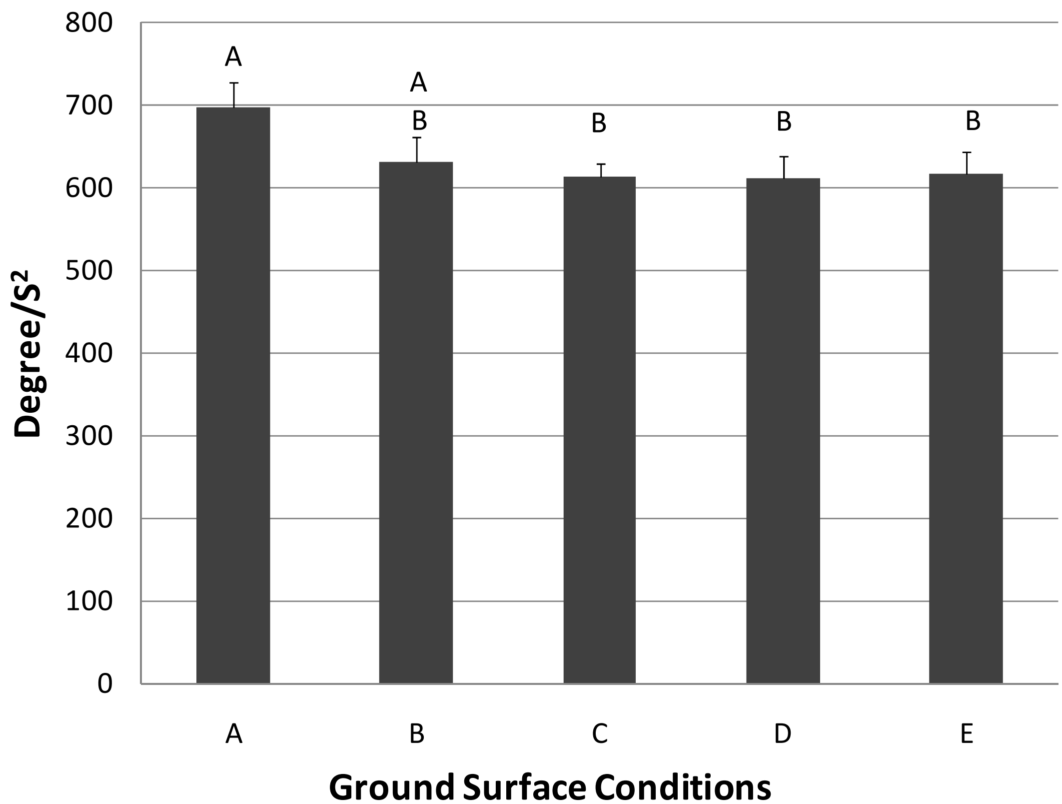

Figure 3: Effect of CONDITION on maximum sagittal acceleration during load lifting task. The letters above each column are from the Tukey-Kramer post hoc test. Different letters represent accelerations that are statistically different from one another.

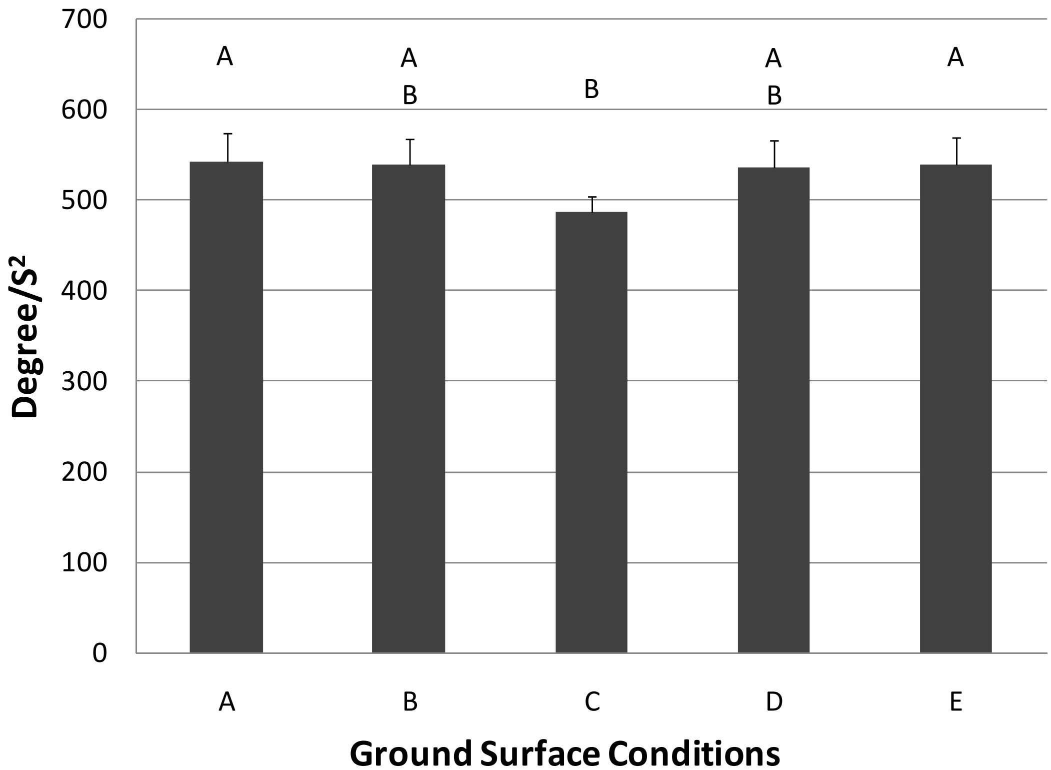

Figure 4: Effect of CONDITION on maximum sagittal deceleration during load lowering task. The letters above each column are from the Tukey-Kramer post hoc test. Different letters represent decelerations that are statistically different from one another.

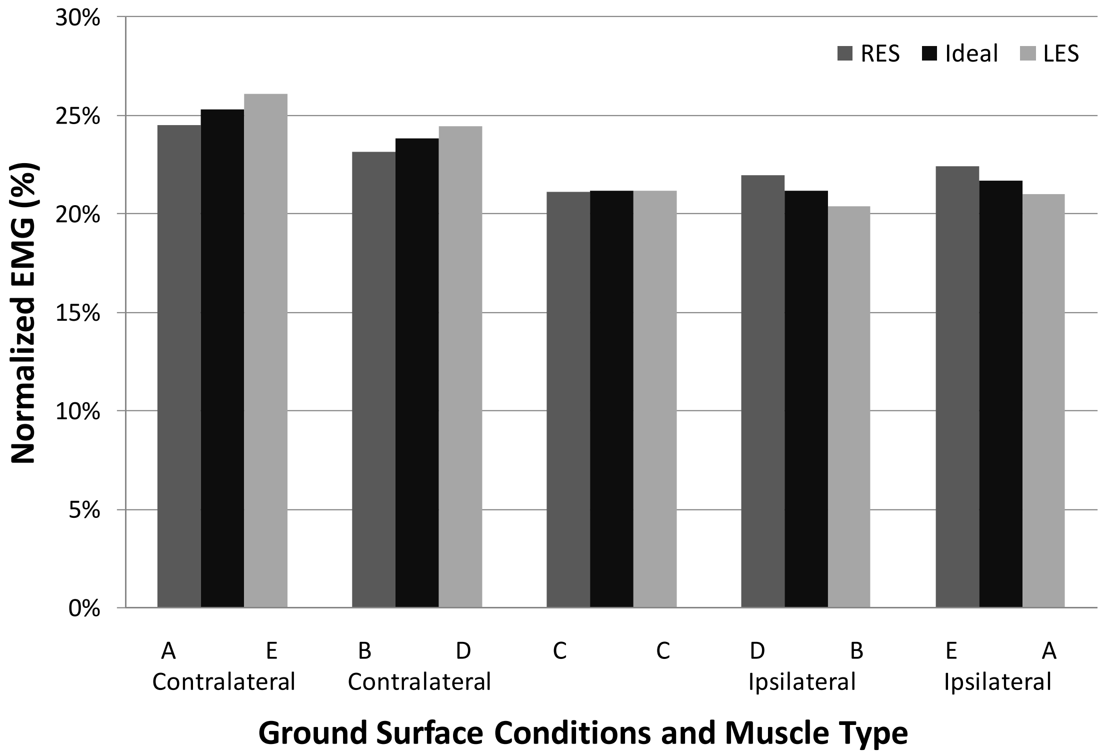

Figure 5: Effect of CONDITION and muscle working type on the erector spinae muscle activity.