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The effect of sinusoidal rolling ground motion on lifting biomechanics

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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 10 kg) and five ground moving conditions. Each ground moving condition was specified by its ground angular displacement and instantaneous vertical acceleration: 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. 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°/s^2 vs. 612–617°/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 (538–542°/s^2 vs. 487°/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.

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 did not 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

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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 120 m 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 accuracy 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 5 s). 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; 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°, 10°, 20° and 30°) 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° and 30°). 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 (Fig. 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 s. Two plastic crates (33 cm × 33 cm × 28 cm) with total mass of 5 kg and 10 kg were the loads to be lifted in this experiment. The crate had good handles and the height of handles was approximately 25 cm.

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 conditions 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 (Fig. 1.)