The Effects of Moving Environments on Thoracolumbar Kinematics and Foot Center of Pressure When Performing Lifting and Lowering Tasks

Carolyn A. Duncan, Scott N. MacKinnon, and Wayne J. Albert

The purpose of this study was to examine how wave-induced platform motion effects postural stability when handling loads. Twelve participants (9 male, 3 female) performed a sagittal lifting/lowering task with a 10 kg load in different sea conditions off the coast of Halifax, Nova Scotia, Canada. Trunk kinematics and foot center of force were measured using the Lumbar Motion Monitor and F-Scan foot pressure system respectively. During motion conditions, significant decreases in trunk velocities were accompanied by significant increases in individual foot center of pressure velocities. These results suggest that during lifting and lowering loads in moving environments, the reaction to the wave-induced postural disturbance is accompanied by a decrease in performance speed so that the task can be performed more cautiously to optimize stability.

Keywords: moving environments, postural stability, motion-induced interruptions, manual materials handling, thoracolumbar kinematics, center of pressure
whole body stability through the examination of the center of mass (CoM) and CoP affected by the complex mechanism involved with maintaining postural stability in moving environments or events such as MII. Therefore, the purpose of this study was to examine the effects of wave-induced ship motions and MII on trunk kinematics and individual foot CoP when performing a sagittal lifting task. This research had the following working hypotheses:

- \( H_1 \): Ship motion magnitude will significantly increase the occurrence of MIIs while performing MMH tasks.
- \( H_2 \): Ship motion magnitude will significantly affect CoP and thoracolumbar kinematics during an MII event while performing MMH tasks.
- \( H_3 \): Ship motion magnitude will significantly affect CoP and thoracolumbar kinematics while performing uninterrupted MMH tasks.

**Methods**

**Participants**

Twelve participants (nine male, three female; stature 160.07 ± 50.79 cm, mass 82.42 ± 17.20 kg, and age 28.92 ± 8.26 years old) participated in this study. Participants were recruited from naval personnel currently on leave in Halifax, Nova Scotia, by Defense Research and Development Canada (DRDC). All participants were free of any known musculoskeletal diseases or injuries. The study was approved by the Memorial University of Newfoundland’s Ethics Board.

**Procedures**

Each participant performed a continuous lifting and lowering task during four collection periods each on separate days. The participant was asked to lift a load directly to and from a shelf 72 cm high and 60 cm in front of them. Throughout the task the participant was asked to keep their feet shoulder width apart and parallel to the shelf in front of them. To ensure participants remained in the same position throughout the task they were asked to keep their toes on a line 60 cm from the shelf at all times. To facilitate accurate box placement during lifts, locations of the origin and destination of the lift were clearly marked on the floor and surface of the shelf. Lifts and lowers were performed consecutively over a period of 5 min at a rate of 3 lifts/min and 3 lowers/min. The participant was free to adopt any lifting/lowering style.

The collection periods took place on the research ship, the CFAV Quest. The baseline condition, during which there was no motion, took place while the research vessel was tied up in port the day before departure. Clearly, it was impossible to estimate beforehand the sea conditions that would be encountered. Subsequently, platform motions while at sea were grouped into low and high motions based on significant wave heights reported at the time of data collection. Significant wave height refers to the average apparent height of the 1/3 highest waves in an irregular pattern (International Towing Tank Conference (ITTC) Dictionary of Ship Hydrodynamics). Significant wave height data were determined from wave data collected from three different wave buoys deployed near the vessel. The low motion session (approximate significant wave height of 3 m) was performed over two consecutive days. The high motion condition (approximate significant wave height of 5.0 m) was also performed over two consecutive days later in the sea trials. The low and high motion trials were collected at sea approximately 100 miles south of Halifax Harbor. The postmotion condition, during which there was also no motion, took place during the final day of the collection period on the ship while it was anchored in a sheltered area in St. Margaret’s Bay, Nova Scotia, approximately 50 km west of Halifax. During each motion condition, two lift/lower conditions were collected. Participants lifted while facing the bow (front of vessel) and while facing the starboard (right side of vessel). The direction that the participants faced was randomized to limit order effects.

The four collection periods thus resulted in six lifting/lowering conditions and included:

1. Baseline
2. Low motion (bow)
3. Low motion (starboard)
4. High motion (bow)
5. High motion (starboard)
6. Postmotion exposure

**Experimental Measures**

An AcuPath Industrial Lumbar Motion Monitor (LMM; Chattecx Corporation, USA) was employed to measure the thoracolumbar displacement-time histories in three planes: flexion-extension movements in the sagittal plane, rotation about the longitudinal axis, and lateral bending within the frontal plane. This exoskeleton weighs approximately 1.5 kg and is secured via straps around the chest, waist, and hips to the participant’s body (Figure 1). The LMM was calibrated following manufacturer’s instructions and data were collected at a rate of 60 Hz. The velocity-time profiles were derived using a first-order differentiation technique.

Foot CoP velocity for each foot was calculated using the F-Scan mobile resistive based insole foot pressure system (TekScan Inc., Boston MA). Each insole was cut to the participant’s individual shoe size and worn in standard running shoes free of any specially designed insoles. Sensors were calibrated according to manufacturer’s instructions in a stationary environment before data collection. The system was worn by the participant for 5–10 min before calibration to allow the sensors to stabilize to the temperature and environment within the shoe (Luo et al., 1998; Mueller & Strube, 1996).

A custom-built motion pack (National Research Council, St. John’s Newfoundland) was placed near the
participant to monitor ship motion during the procedure. The motion pack measures three linear accelerations (heave, surge, and sway) and three angular velocities (pitch, roll, and yaw) relative to the platform motion. These data were recorded by a microcomputer via a serial connection.

A VHS video camera recording at 60 Hz and equipped with sound was mounted at a 45° angle, providing an adequate view of the participant while performing all the tasks. This record was later used to identify whether a lift/lower was executed with or without a MII.

Data Acquisition
The LMM, F-Scan, and motion pack collection devices were synchronized at the beginning of each trial. The F-Scan was preprogrammed to cease recording after a specified period of time. Once the F-Scan had stopped recording, both the LMM and motion pack were subsequently stopped manually.

Data Analysis
The LMM, F-Scan, and motion pack data were time normalized to 60 Hz, cut to 2 min lengths, and outputted as a single comma-separated variable (CSV) file using Matlab (The Mathworks Inc.) programming software. The MII during each trial were identified with the aid of the video data. The literature defines an MII as “an occasion when a person would have to stop working at their current ship board task and either change their stance, take a step or hold on to some convenient anchorage to prevent loss of balance” (Baitis et al., 1984). For the purpose of this study, an MII was considered to be any point at which the participant moved their feet from the reference position or grabbed a nearby anchorage (e.g., the table). Interrupted events consisted of data 0.5 s before the MII event to the time recovery when the subject has returned to their reference position. Mean and peak LMM angular velocities and individual foot CoP velocities in anterior-posterior and medial-lateral directions were calculated for both uninterrupted lifts and lowers and MII lift/lowers. Uninterrupted data were compared between motion conditions for each lifting and lowering task. The MII data were compared with corresponding uninterrupted motion condition data as well as to baseline and postmotion data.

Statistical Analysis
An analysis of variance (ANOVA) was performed to identify significant differences in thoracolumbar and foot CoP velocities between motion conditions factor (six levels) and the effects of the MII occurrence upon the lift. Tests to ensure the assumptions of parametric statistics were conducted. A 0.05 level of significance was used.

Results
Lifting
Table 1 reports mean and peak thoracolumbar velocities during uninterrupted lifting. During the high motion condition, mean and peak sagittal thoracolumbar velocities were significantly lower than baseline.

Significant differences in foot CoP velocities between several motion conditions and baseline were found during lifting (Table 1). P-Values for comparisons are shown in Table 2. Left and right peak anterior-posterior velocities during high (bow and starboard) postmotion conditions were significantly greater than baseline velocities. Right foot anterior-posterior velocity during the low motion starboard condition was significantly greater. Peak anterior-posterior velocities during the high motion starboard condition were also significantly greater than low (bow and starboard) and postmotion conditions.

Left foot peak medial-lateral velocity during the high motion starboard condition was significantly greater than baseline and both low motion conditions. Right foot peak medial-lateral velocity during the high motion bow condition was also significantly greater than baseline.
Table 1  Mean and peak thoracolumbar velocities (degrees per second) and peak CoP velocities with standard deviations (in parentheses) during uninterrupted lifting

<table>
<thead>
<tr>
<th>Motion</th>
<th>Thoracolumbar</th>
<th>CoP</th>
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<tbody>
<tr>
<td></td>
<td>Lateral</td>
<td>Sagittal</td>
</tr>
<tr>
<td>Baseline</td>
<td>1.41 (0.32)</td>
<td>11.06 (4.96)</td>
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<tr>
<td>Low Motion (Bow)</td>
<td>1.21 (0.28)</td>
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<tr>
<td>Low Motion (Starboard)</td>
<td>1.17 (0.35)</td>
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<tr>
<td>High Motion (Bow)</td>
<td>1.41 (0.44)</td>
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<td>High Motion (Starboard)</td>
<td>1.29 (0.51)</td>
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</tr>
<tr>
<td>Post Motion</td>
<td>1.26 (0.41)</td>
<td>6.91 (2.84)</td>
</tr>
</tbody>
</table>

*p < 0.05. **p < 0.05. ***p = 0.05.
Effects of Moving Environments

Table 2  *P*-Values for statistical comparisons between all testing conditions during uninterrupted lifting

<table>
<thead>
<tr>
<th>Condition</th>
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<th>Anterior-Pe</th>
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<td>1.000</td>
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<tr>
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<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
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<td>1.000</td>
<td>0.465</td>
<td>0.262</td>
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<tr>
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<td>0.503</td>
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<td>LMB vs Postmotion</td>
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<td>1.000</td>
<td>0.782</td>
<td>0.600</td>
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<td>0.405</td>
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<td>0.994</td>
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<td>HMS vs Postmotion</td>
<td>0.960</td>
<td>1.000</td>
<td>0.997</td>
<td>0.960</td>
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Note. Bold italics indicates significance $p < .05$. LMB = low motion (bow), LMS = low motion (starboard), HMB = high motion (bow), HMS = high motion (starboard).

Lowering

Table 3 reports mean and peak thoracolumbar velocities during uninterrupted lowering. During high and postmotion conditions, mean and peak sagittal thoracolumbar velocities were significantly lower than baseline. Mean and peak sagittal velocities during the postmotion condition were also significantly lower than the low motion starboard condition.

Between high and low motion conditions, significant differences were found only in peak anterior-posterior velocities (Table 4). Peak left and right foot anterior-posterior velocities during all motion and postmotion conditions were significantly greater than the baseline condition (Table 3). Left and right foot anterior-posterior velocities during the high motion starboard condition were also significantly greater than both low and postmotion conditions.

Left and right foot peak medial-lateral velocities during the high motion bow condition were significantly greater than baseline medial-lateral velocities. Left foot medial-lateral velocity during the high motion starboard condition was also significantly greater than those observed during the baseline condition.

The MII were observed for both lift and lowers; MII rates were 0.1 ± 0.2 MII/min (six total MIIs) and 1.71 ± 1.50 MII/min (94 total MIIs) for low and high starboard tasks, respectively. From a statistical power perspective, statistics could only be performed on the MIIs for the high motion starboard condition.

Significant differences were found between MII and uninterrupted lifting and lowering for both mean and peak lateral and twisting thoracolumbar velocities (Figure 2). *P*-Values for all comparisons are shown (Table 5). During MII lateral and twisting, thoracolumbar velocities were significantly higher than during uninterrupted lifts and lowers in the high motion starboard condition (Figure 2). Left and right foot anterior-posterior CoP velocities were significantly greater than peak velocities observed during the high motion starboard condition (Figure 3).

Discussion

The purpose of this study was to examine the effects of wave-induced ship motions and MII on trunk kinematics and individual foot CoP when performing a sagittal lifting task. Results of the study suggest that wave-induced ship motions could have a significant effect on both these variables, particularly during the occurrence of an MII.

During the uninterrupted lifting and lowering tasks, there were significant increases in peak CoP velocities in both the anterior-posterior and medial-lateral directions in high motion conditions. These changes in CoP were accompanied by significant decreases in thoracolumbar velocities. While lifting in high motion conditions, mean and peak sagittal velocities were significantly lower than those observed during baseline lifting and lowering. Mean and peak sagittal velocities while lifting and lowering...
<table>
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<tr>
<td></td>
<td>Lateral</td>
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<tr>
<td>Baseline</td>
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<td>Low Motion (Bow)</td>
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<td>High Motion (Starboard)</td>
<td>1.48 (0.58)</td>
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<tr>
<td>Post Motion</td>
<td>1.21 (0.44)</td>
<td>6.81 (3.24)</td>
</tr>
</tbody>
</table>

*aSignificantly different from baseline (p < 0.05). bSignificantly different from low motion conditions (p < 0.05). cSignificantly different from postmotion (p = 0.05).
<table>
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<tr>
<th>Condition</th>
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<th>Anterior-Posterior</th>
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<td>HMS vs Postmotion</td>
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<td>0.979</td>
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</table>

*Note: Bold italics indicates significance $p < .05$. LMB = low motion (bow), LMS = low motion (starboard), HMB = high motion (bow), HMS = high motion (starboard).*

**Figure 2** — Comparison of mean and peak thoracolumbar velocities during motion-induced interruptions and corresponding uninterrupted high motion starboard condition when lifting and lowering. *Note: HMS = high motion starboard; MII = motion-induced interruption. *Significantly different from MII ($p < .05$).*
during the low motion (bow and starboard) condition were also lower than baseline values but these differences were not significant. These findings suggest that the height of the wave increased, the speed at which the MMH task is performed must decrease so that postural stability can be maintained. Although not examined in this study, an increased wave height may cause a change in lifting to a slower technique that protects against loss of balance. For example, the person may switch to a squat or semisquat technique as opposed to a stoop technique, similar to those seen in studies that examined lifting by participants who do not have knowledge of the load characteristics being lifted (Commissaris & Toussaint, 1997; Heiss et al., 2002).

Reduced thoracolumbar velocities in the motion conditions are likely a protective mechanism mediated by an increase in core or trunk stability. However, further investigation of trunk stiffness properties is required. One should also assume that wave height and period will impact these changes in trunk kinematics and kinetics. Increased CoP velocities are likely related directly to kinematic characteristics of the floor motions or may indirectly reflect a compensation strategy for improved stability, given the reduced inertial trunk properties.

The results from this study are similar to those found in previous studies done in simulated motion environment. Matthews et al. (2007) found that when lifting in pitch, roll, and quartering sea conditions, sagittal thoracolumbar velocities were significantly lower than during no motion conditions. The exception was that no significant differences were found in mean or peak lateral or twisting velocities between baseline and motion conditions. This may be attributed to the differences in motion profiles.

The participants in this study were exposed to accelerations about all 6 degrees of freedom. As a result, movement within 1 df may inadvertently counteract a shift in CoM from a perturbation in another direction, thus eliminating the need to use additional trunk movements to counteract the perturbation and maintain postural stability. This may also make the detection of condition differences difficult from a statistical perspective.

When lifting and lowering tasks were interrupted by an MII during the high motion starboard condition, mean and peak thoracolumbar lateral and twist velocities were significantly increased. During MII, mean and peak sagittal velocities were also higher than those observed during the corresponding uninterrupted high motion starboard, although not significant. Duncan et al. (2007) observed that when an MII is overcome while performing a lifting or lowering activity, there is a sudden trunk extension to return the trunk to an upright posture followed by a foot repositioning. Because the thoracolumbar velocities are increased as a result of an MII event, this compensatory reaction to reestablishing postural stability will likely increase the risk of low back injury.
The following conclusions can be made from this study. Wave motions have a significant effect on thoracolumbar kinematics. When lifting/lowering loads in motion-rich environments, increases in foot CoP velocities accompanied by decreases in thoracolumbar velocities were observed, suggesting that in motion environments the participant adopts a compensatory strategy for lifting/lowering. Motion-induced interruptions during the execution of lift/lowering tasks further increase foot CoP velocities and thoracolumbar velocities and likely reflect occasions for high risk of low back injury.

**Limitations**

When interpreting the results of this research the following limitations should be considered.

(a) Sample size and diversity within in the sample: Due to the limited accommodations aboard the vessel and the available naval personnel, the experimental sample size was smaller and more diverse than originally expected. Diversity of the sample across all anthropometric variables was great and may account for the unequal variances found for many of the dependent variables. However, appropriate statistical measures were used to adjust for this variability when necessary.

(b) Subject experience: As with many of the anthropometric variables, amount of the sea experience was very diverse. Originally, an inclusion requirement of the study was that subjects have at least 1 y of sea experience; however, because of the limited availability of subjects that met this criterion within the subject pool, exceptions had to be made. As a result, many of the subjects had limited sea experience whereas some had many years of experience. This factor may have affected how the subjects reacted to the ship motion. Experienced naval personnel may have accommodation strategies owing to their habituation to sea environments that may lead to less postural adaptations required to maintain postural stability. However, it is hoped that the unfamiliar nature of the tasks being performed by the subjects limited the effect of learning experience.

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**References**


