Towards ambulatory assessment of spinal loading in the field

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2010

Chapter 4

Effect of ship motion on spinal loading during manual lifting

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Ergonomics (2008), 51(9), 1426-1440

ABSTRACT

This study investigated the effects of ship motion on peak spinal loading during lifting. All measurements were done on a ship at sea. In 1-minute trials, which were repeated over a wide range of sailing conditions, subjects lifted an 18 kg box five times. Ship motion, whole body kinematics, ground reaction forces and electromyography were measured and the effects of ship motion on peak spinal moments and compression forces were investigated. To investigate whether people time their lifts in order to reduce the effect of ship motion on back loading, trials were performed at a free and at a constrained work pace (lifting every 10 seconds). With increase of the (local) vertical ship acceleration, increased moments and compression forces were found. Furthermore, lifting at a free work pace did not result in smaller effects of ship motion on spinal moments and compression forces than working at a constrained work pace.

INTRODUCTION

Performing heavy work (such as lifting) on a ship is associated with a high prevalence of musculoskeletal problems. For a population of fishermen in Sweden (Törner et al., 1988) and North Carolina (Lipscomb et al., 2004), the year-prevalence of musculoskeletal problems was reported to be 70% and 83%, respectively. In both populations, about two-thirds of the complaints were related to the low back. Furthermore, lifting activities and ship motion were reported by the fishermen as the main cause of high workload (Törner et al., 1988).

Many previous studies have demonstrated that lifting is an important risk factor for work-related low back pain (Norman et al., 1998; Hoogendoorn et al., 1999; Kuiper et al., 1999; Lötters et al., 2003; Kuiper et al., 2005) and that this is probably due to the relatively high spinal forces in lifting (Marras et al., 1999b; Faber et al., 2006). Those forces can exceed the tolerance level of the intervertebral joints (Waters et al., 1993).

Ship motion may affect low back loading during lifting (Kingma et al., 2003) and thereby affect the risk for the occurrence of low back pain. Depending on the timing of a lifting movement, ship motion can either increase or decrease low back loading. When considering only the vertical acceleration, one could expect that the required muscular effort increases when the ship accelerates upwards and decreases when the ship accelerates downwards. However, when a ship is sailing, it also accelerates in horizontal direction and it rotates around its axes. These motions can also have an effect on low back load, and the combined effect of ship motion may be hard to predict.

To the authors' knowledge only one study (Törner et al., 1994) investigated the effect of ship motion on low back loading during lifting on a ship, but this study was performed with only one subject, in one sailing condition and without measurement of trunk muscle activity. Kingma et al. (2003) performed a simulation study in which the effect of ship acceleration on low back loading during lifting was predicted by applying ship accelerations to lifting movements that had been measured under stationary conditions. Unfavourable timing of the lift resulted in a predicted increase in total net moment at the low back of up to

15%. Furthermore, it was concluded that a substantial reduction of low back loading by favourable timing would be very difficult to achieve.
The question remains whether the outcomes of this simulation study are realistic, because changes in lifting behaviour as a result of the motions of the ship were not taken into account. It could be, for example, that subjects adapt their body inclination angle in response to changes in ship roll angle. Additionally, abdominal co-activation and the muscle recruitment pattern (which was not incorporated in the simulation study) could also change due to ship acceleration, thereby affecting low back loading.
The aim of present study was to find out to what extent ship motion affects low back loading in terms of moments and spinal forces at the L5-S1 joint during manual lifting on a ship at sea. Furthermore, it was investigated whether subjects avoid ship motion that increases low back loading, by comparing lifting at a fixed pace to freely timed lifting.

METHODS

Subjects

After signing an informed consent, nine healthy males (average ± SD: age 35 ± 13 years, weight 95 ± 15 kg, height 184 ± 5 cm) participated in the experiment. They all had at least 6 months of experience of working on a ship.

Procedure

The experiment took place on the Royal Netherlands Navy training vessel "Van Kinsbergen", which is 42 m long and 9 m wide (Figure 4-1). The room where the experiment was performed was located close to the (forward-backward) centre of the ship. During the experiment subjects stood on a large force plate and they were facing larboard (the positive y-direction, see Figure 4-1).

Figure 4-1. *Photograph of the Royal Netherlands Navy training vessel "Van Kinsbergen" on which the experiment took place. The local coordinate system of the ship, which was used in the present study, is indicated.*

All of the experiments were performed while sailing on open water. As weather conditions could not be controlled, no attempts were made to standardise ship motion over subjects. Rather, it was intended to measuring under a wide range of sailing conditions. The magnitude of the ship motion was varied by repeating the lifting trials at different locations at sea (out at sea or near the coast) and by varying sailing speed (5 or 10 knots) and sailing direction relative to the direction of the waves. Subjects lifted an 18 kg box. The initial handle height of the box was 29 cm above the force plate and the subjects were free to choose a comfortable, but forward directed foot placement for each trial. As shown in Figure 2-4 the box was lifted either from a symmetric position (right in front of the subjects) or from an asymmetric position (30° rotated to the right).

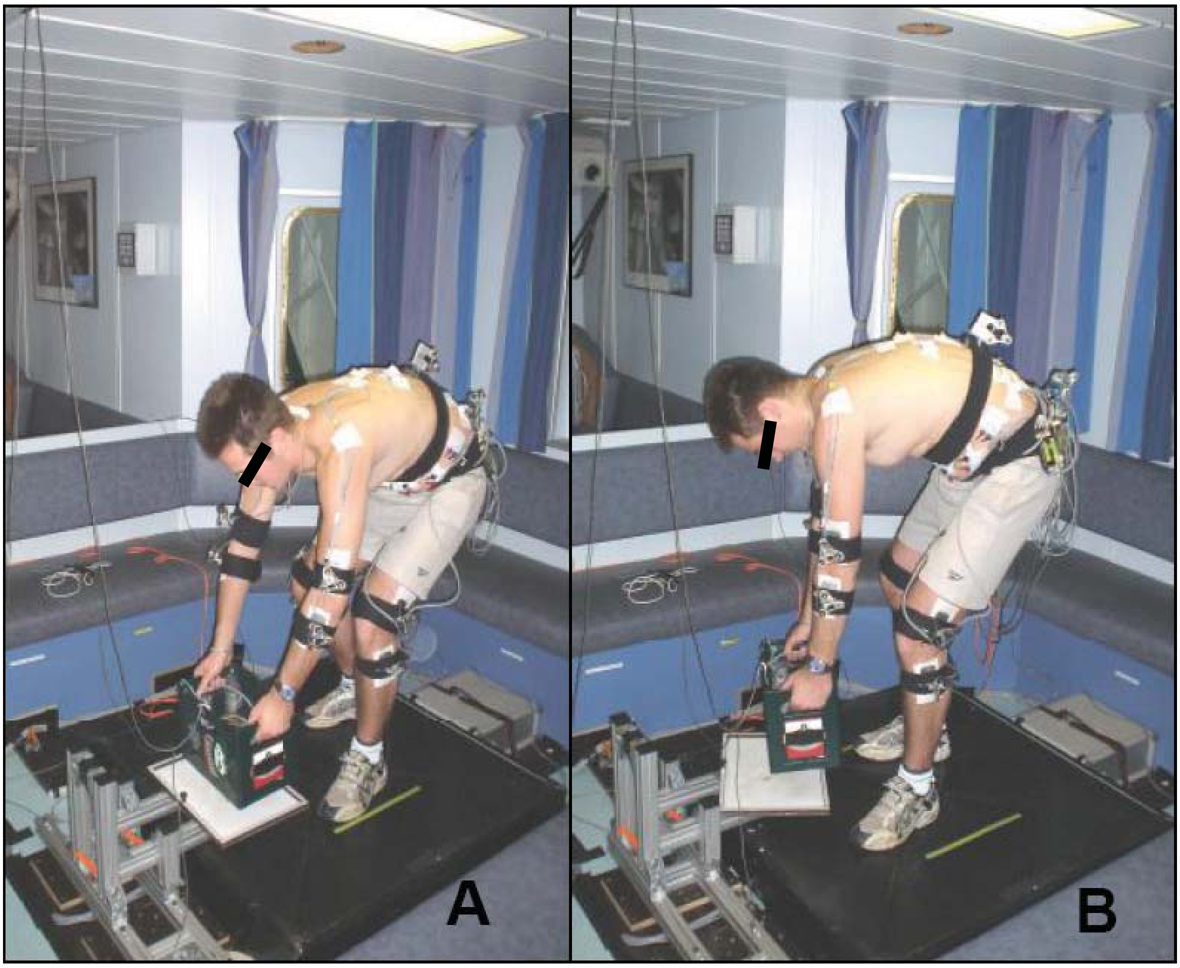

Figure 4-2. Photographs of the symmetric (A) and asymmetric (B) lifting tasks that were performed by the subjects during the experiment.

The effect of timing on low back loading was tested by performing both the symmetric and asymmetric lifts at a free and at a constrained work pace. In each of those four conditions, five lifts were performed. In the “free work pace” condition subjects were free to lift and lower the box five times somewhere within 1 minute of measurement time. In the “constrained work pace” condition subjects had to lift the box five times, separated by 10 s, on command of the experimenter. After having performed the 20 lifts (four conditions times five lifts) the ship changed its sailing direction and/or sailing speed and/or location at sea.

Three-dimensional linked segment model

A dynamic three-dimensional linked segment model (LSM), described in detail and internally validated (by comparing a top-down to a bottom-up calculation of net moments) by Kingma et al. (1996) was used to estimate net moments at the level of the L5-S1 joint. This model calculates the net moment around the L5-S1 joint on the basis of external forces, kinematics of (body) segments and anthropometrical data. In the present study, whole body analysis was applied to allow calculation of the net moments starting from the feet (bottom-up analysis) as well as starting from the box that was lifted (top-down analysis). Kinematics of the box, lower arms (+ hands), upper arms, trunk (+ head), pelvis, upper legs and lower legs (+ feet) were measured using cluster marker constructions that consisted of two metal plates connected with a double hinge joint. One of the metal plates was taped and strapped to the segment with an elastic neoprene band and on the other plate three LED markers were attached (see Figure 4-2). The positions of the markers were measured in 3D at 50 Hz using Optotrak (Northern Digital Inc., Canada). Two arrays of Optotrak cameras were attached to an aluminium frame which was securely clamped between the floor and ceiling of the measurement room. Markers on each segment were related to anatomical landmarks by making a short recording while pointing at each landmark (Cappozzo et al., 1995) with a pointer containing six markers. Mass, position of the centre of mass and the moments of inertia of each segment were calculated using regression equations published by McConville & Churchill (1980). The ground reaction force (the external force at the feet) was measured by a custom-made 1 x 1 m strain gauge force plate at a sample rate of 200 Hz. Force plate data were synchronised to the Optotrak system and stored.

Because the measurements in the present study were done in a moving environment, kinematic and force plate data were corrected for ship motion. Ship motion was measured using a custom made five degrees of freedom ship motion measurement unit that was based on accelerometer and gyroscope signals. Local axes of the ship were chosen as follows: X-axis forwards, the Y-axis to larboard (the left side of the ship) and the Z-axis upwards (Figure 4-1). The ship motion measurement unit measured 3D linear accelerations. Furthermore, angular velocity and (calculated) angles and angular accelerations were obtained for rotations around the X- (roll) and the Y-axis (pitch) of the ship. The system did not provide data about the movement around the Z-axis (yaw), but because the ship was sailing straight ahead during the measurements, motions around the Z-axis probably did have a negligible influence on the low back load (see the limitations section at the end of the discussion for more support of this assumption). The ship motion data were measured at 500 Hz and synchronised to the Optotrak system and stored. The ship motion measurement unit was placed right behind the force plate on which the subjects were standing during the experiment (Figure 4-2).

Correction of kinematic data

For the calculation of the motions of the segments relative to the world (which is needed to correctly calculate the net moments), the ship motion was added to the motions of the segments as follows:

$$\boldsymbol{\omega}_i' = \boldsymbol{\omega}_i + \boldsymbol{\omega}_{\mathbf{ship}}$$

$$\mathbf{a}_i' = \mathbf{a}_i + \mathbf{a}_{\mathbf{ship}}$$

where $\boldsymbol{\omega}_{ship}$ and $\mathbf{a}_{ship}$ are, respectively, the angular velocity and the linear acceleration of the ship relative to the world, $\boldsymbol{\omega}_i$ and $\mathbf{a}_i$ are, respectively, the angular velocity and the linear acceleration of centre of mass of segment *i* in the local axes of the ship and $\boldsymbol{\omega}_i'$ and $\mathbf{a}_i'$ are, respectively, the angular velocity and the linear acceleration of segment *i* relative to the world. It must be noted that $\mathbf{a}_{ship}$ consists of the actual acceleration of the ship relative to the world plus the acceleration due to gravity.

Correction of force plate data

Because the cover of the force plate (i.e. the part between the strain gauges and the subject) had a mass of itself, the ship motion resulted in variation in the measured ground reaction forces and point of application, not only due to the acceleration of the subject, but also due to the acceleration of the force plate cover. Because these forces are directly related to the accelerations of the ship, measured forces and the point of application of the ground reaction force could be corrected for ship motion. The force vector due to the acceleration ($\mathbf{F_p}$) of the force plate cover mass was calculated by multiplying the mass of the force plate cover (m_{fp}) with the linear acceleration of the ship ($\mathbf{a}_{ship}$):

$$\mathbf{F_p} = m_{fp} \cdot \mathbf{a}_{\mathbf{ship}}$$

This force vector was then projected from the centre of mass of the force plate cover to the planes in which each of the three force components were measured, perpendicular to the direction of the measured force. After projection, $\mathbf{F_p}$ could be distributed over, and subtracted from, the signal of the separate strain gauges.

Before using the corrected kinematic and force plate data as input in the LSM, the data were low-pass filtered at 5 Hz. A global equation of motion (rather than a segment by segment calculation) was used, as described by Hof (1992) with, as a small modification, the addition of the ground reaction moment about the vertical measured by the force plate:

$$\mathbf{M_{L5-S1}} = -\mathbf{M_g} - (\mathbf{r_g} - \mathbf{r_{L5-S1}}) \times \mathbf{F_g} + \sum_{i=1}^{q} [(\mathbf{r}_i - \mathbf{r_{L5-S1}}) \times m_i(\mathbf{a}'_i)] + \sum_{i=1}^{q} \mathrm{d}(\mathrm{I}_i \omega'_i)/\mathrm{dt},$$

where $\mathbf{M_{L5\text{-}S1}}$ is the net moment at the L5-S1 joint, $\mathbf{M_g}$ is the ground reaction moment, $\mathbf{r_g}$ is the position vector of the point of application of the ground reaction force, $\mathbf{r_{L5\text{-}S1}}$ is the position vector of the L5-S1 joint, $\mathbf{F_g}$ is the ground reaction force, q is the number of segments, $\mathbf{r}_i$ is the vector to the centre of mass of segment i , m_i is the mass of segment i, d(...)/dt is the time derivative of the expression within parentheses, I_i is the inertia tensor of segment i. Note that, in this equation, there is no separate term for the moment due to gravity because, as mentioned before, gravity is incorporated in the acceleration of the segments. For top-down analysis the moment terms due to the force plate (first two terms) were not taken into account. The external forces and moments acting on the hands as a result of interaction with the box were not directly measured. Instead, the effect of the acceleration of the box was calculated by treating it as an additional segment with a point mass positioned in the centre of the box. With this analysis it is only possible to calculate the effect of the box on the net moments when the box makes no contact with the support surface from which it is lifted. Therefore, for the top-down analysis, net moments were only calculated after lift-off.

Three-dimensional EMG-Driven Trunk Model

After shaving the skin and cleaning with alcohol, 14 pairs of surface electromyografic (EMG) electrodes (Blue Sensor; Ag-AgCl electrodes;

interelectrode distance, 20 mm) were bilaterally attached over three locations of the back muscles: the iliocostalis lumborum (6 cm lateral to L2), the longissimus thoracis pars lumborum (3 cm lateral to L3) and the longissimus thoracis pars thoracis (4 cm lateral to T9) and over four locations of the abdominal muscles: the rectus abdominis (at the level of the umbilicus), the internal oblique (just superior to the inguinal ligament), the anterior external oblique (approximately 15 cm cranial of the anterior iliac spine) and the lateral external oblique (midaxillary line, halfway between the iliac crest and the lowest edge of the rib cage). The EMG data were recorded (Porti-17TM; TMS, Enschede, The Netherlands; input impedance > 10 Ω; common mode rejection ratio (CMRR) > 90 dB), A–D converted (22 bits at 1000 Hz), and stored synchronised to the Optotrak, ship motion and force-plate data. Offline, EMG signals were high-pass filtered (30 Hz), full-wave rectified, and low-pass filtered at 2.25 Hz (Potvin et al., 1996). Subsequently, EMG data were normalised to maximum voluntary contractions (defined as 2 s of maximum activation for each muscle from a series of maximum voluntary trunk extensions, flexions, lateral flexions and axial rotations), non-linearly transformed into an estimate of muscle activation as described by Potvin et al. (1996) and used as the input of an EMG-driven trunk muscle model. This model has been described in more detail elsewhere (van Dieën, 1997; van Dieën & Kingma, 2005) and consists of a compilation of anatomical data described by Stokes & Gardner-Morse (1995) for the back muscles and by McGill (1996) for the abdominal muscles. The transversus abdominis muscle and the psoas major muscle were excluded because it is unlikely that their activity can be estimated reliably from surface EMG data and because their moment-producing capacity is limited. The latissimus dorsi muscle was omitted because a reliable indication of its force would require modelling the shoulder in detail and because its capacity to generate an extensor moment at the lumbar spine is only small (Bogduk et al., 1998). After exclusion of the above-mentioned muscles, the model consisted of 90 muscle slips crossing the L5–S1 joint. The model was scaled to individual body height. For muscle slips crossing the L4 and T12 levels, nodes were used as points about which these long muscles were wrapped. In this way, the muscles followed the lumbar curvature during motion. After assigning each of the 90 muscle slips to one of the 14 EMG signals, muscle forces were estimated as the product of the assumed muscle maximum stress (a single value for all muscles, which was adjusted for each subject to obtain the best fit between net moments and muscle moments), normalised EMG amplitude, and correction factors for the instantaneous muscle length (Woittiez et al., 1984) and contraction velocity (van Zandwijk, 1998). The muscle lengths and contraction velocities were calculated on the basis of thorax orientation relative to the pelvis orientation. Finally, to obtain compression and shear forces at the L5–S1 intervertebral joint, muscle forces and net reaction forces were summed after being projected on the axis system connected to the L5-S1 disk. For convenience, shear forces pushing the trunk forward were indicated as positive and absolute values were taken for lateral shear forces.

Statistical analyses

To check the internal validity of the LSM, as applied on a moving ship, the correlation between the total net moments obtained from the top-down and the bottom-up analysis was calculated. To quantify the effect of ship motion, only those ship motion variables that directly affect the mechanical loading of the body were considered for use as independent variables, i.e. the ship motion variables that appear in the equation of motion: linear acceleration, angular velocity and angular acceleration. For each component of each of these variables, the variation in the magnitude was calculated for each 1-minute trial. This value was calculated by subtracting the mean and subsequently calculating the average absolute value (AAV) of the resulting signals.

The peak total net moment per trial was determined over the five lifting movements that were performed. Furthermore, at the instant of peak total net moment, the following dependent variables were calculated: the L5-S1 compression and shear forces, and the abdominal co-contraction (the average over all abdominal EMG signals). In addition, as a measure of timing effects, the instantaneous total ship acceleration (length of the 3D linear acceleration vector) was calculated at the instant of peak total net moment.

A generalised estimating equations (GEE) regression analysis (Liang & Zeger, 1993) was used to test the effect of the ship motion, task symmetry (symmetric vs. 30° asymmetric) and work pace (free vs. constrained) on all of the above-mentioned dependent variables. A GEE regression analysis is comparable to a multiple regression analysis in which there is one dependent variable and multiple independent variables. The reason why a GEE regression analysis was used is because, unlike a multiple regression analysis, it considers measurements within participants as repeated measurements and thus accounts for systematic subject effects. For the ship motion variables, only the ones that had a considerable contribution to the total net moment (at least 1 Nm) were selected to serve as independent variables in the statistical analysis. In the GEE regression analysis the regression equation was defined as:

$$
\begin{aligned}
\textit{Outcome} = \textit{Constant} \quad & + A_1 \quad \cdot \textit{AAV (ship motion parameter 1)} \\
& \ldots \\
& + A_X \quad \cdot \textit{AAV (ship motion parameter X)} \\
& + B \quad \cdot \textit{Work pace (unconstrained = 0, constrained = 1)} \\
& + C \quad \cdot \textit{Symmetry (symmetric = 0, asymmetric = 1)}
\end{aligned}
$$

The compression force was used to construct the GEE regression model. All possible two-way interactions between the independent variables were tested separately and only included in the model when significant. For the other dependent variables a GEE regression model with the same independent variables (and possible interactions) was constructed.

To investigate whether people adjusted body posture to ship motion, an additional GEE regression analysis was performed. To this end, the ship angle at the instant of peak total net moment was used as an independent variable. The body inclination angle (the vector from the centre of pressure on the force plate to the centre of mass of the subject and box in the ship axes system) at the instant of total net moment was used as a dependent variable. The analysis was applied to the rotations around the X- as well as the Y-axis of the ship. For all statistical outcomes a significance level of 5% was used ($p < 0.05$).

RESULTS

There was good agreement between the top-down and bottom-up calculated net moments. The coefficients of correlation (R^2) between the top-down and the bottom-up calculated total net moment and the total net reaction force were, averaged over the experimental trials and over subjects, 0.984 (SD 0.025) and 0.956 (SD 0.034) respectively. As the GEE regression results were similar for the top-down and bottom-up analysis, only results for the bottom-up analysis will be presented.

For the GEE regression analysis, only the linear accelerations were selected to serve as independent variables because the angular velocity and acceleration had a minor effect on the total net moment (i.e., < 0.5 Nm in all trials). In Figure 4-3, an example is presented of the linear accelerations and the total net moments that were observed during an experimental trial. Figure 4-4 shows the AAVs of the 3D linear ship accelerations that occurred during all experimental trials. Generally, the AAVs of the linear accelerations were the highest in the Y-direction and the lowest in the X-direction. Due to variations in weather conditions, the range of accelerations varied across subjects.

Because a high correlation ($R^2 = 0.62$) was found between the AAV of the Z- and X-accelerations, one of these variables had to be excluded from the GEE regression analysis. Because the fit of the GEE regression model for the compression force was better when using AAV of the Z- instead of the AAV of the X-acceleration, the AAV of the X-acceleration was removed from the GEE regression model. For the compression force, none of the interactions reached significance. The resulting GEE regression model and the coefficients for this model are presented in Table 4-1.

For the AAV of the Y-acceleration of the ship no significant effects on the low back load determinants were found. The AAV of the Z-acceleration was significantly related to an increase of the maximum peak total net moment (10.1% per m/s^2 AAV Z-acceleration) over the five lifts within the 1-minute trials. At the instant of maximum peak total net moment, the compression force and the instantaneous total ship acceleration increased with 19.1% and 11.4% per m/s^2 AAV Z-acceleration, respectively. Abdominal co-contraction was not affected by AAV of the Z-acceleration.

Work pace only affected the net total moment: lifting at a constrained work pace resulted in a slightly (1.5%) but significantly higher total net moment than lifting at a free work pace. Work pace did not significantly affect the instantaneous total ship acceleration at the instant of peak net total moment. Asymmetry of the lift did not affect any of the dependent variables.

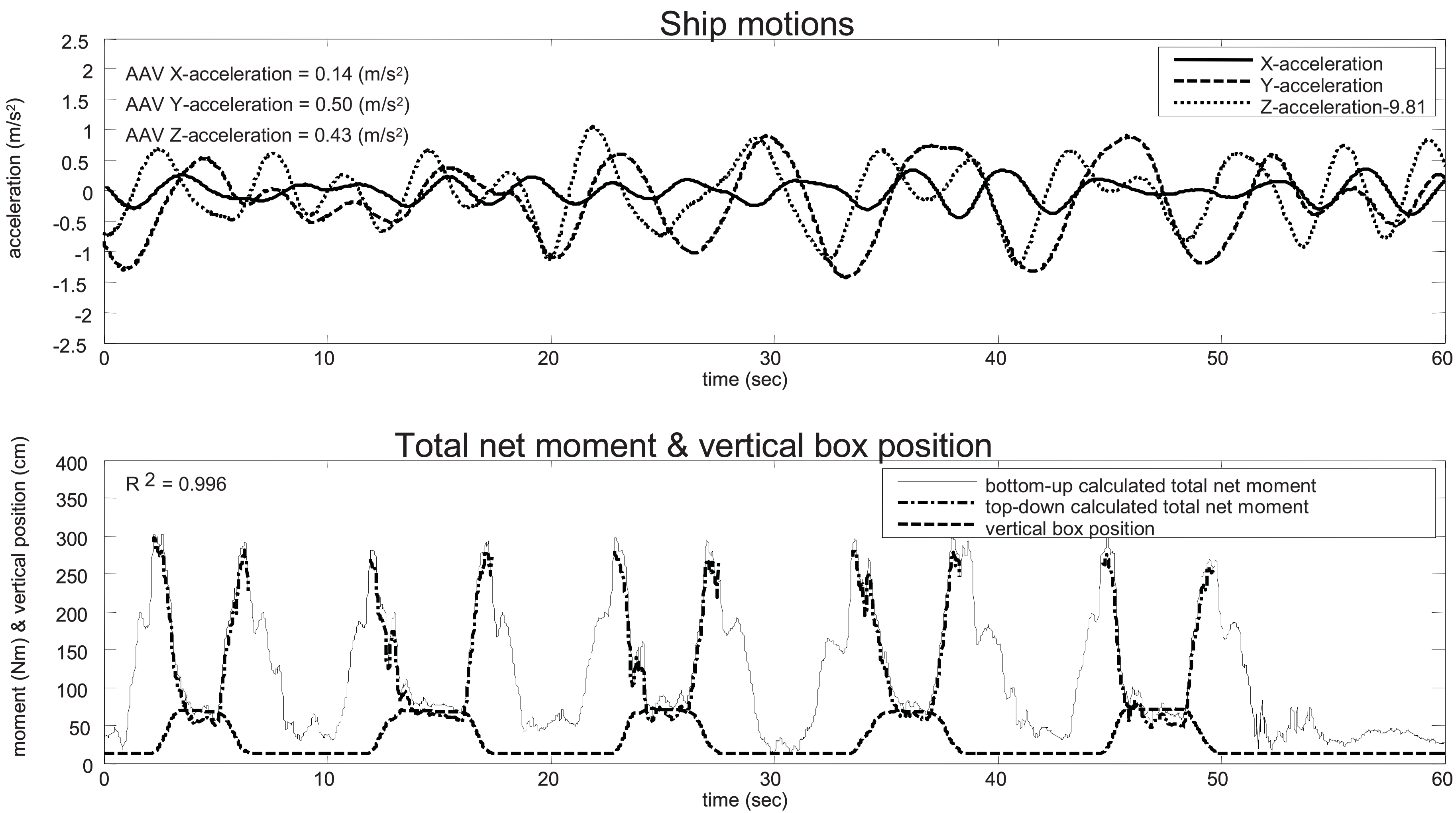

Figure 4-3. *In the upper panel, the linear ship accelerations, measured during an experimental trial, are shown. In the left hand corner the absolute average value (AAV) of these acceleration are indicated. For the same trial, total net moments around the L5-S1 joint calculated with the bottom-up (solid line) and top-down (dashed line) linked segment analysis are shown in the lower panel. Note that the top-down calculated total net moment is only displayed between the start of the lifting movement and the end of the lowering movement (when the box makes no contact with the support surface from which it is lifted).*

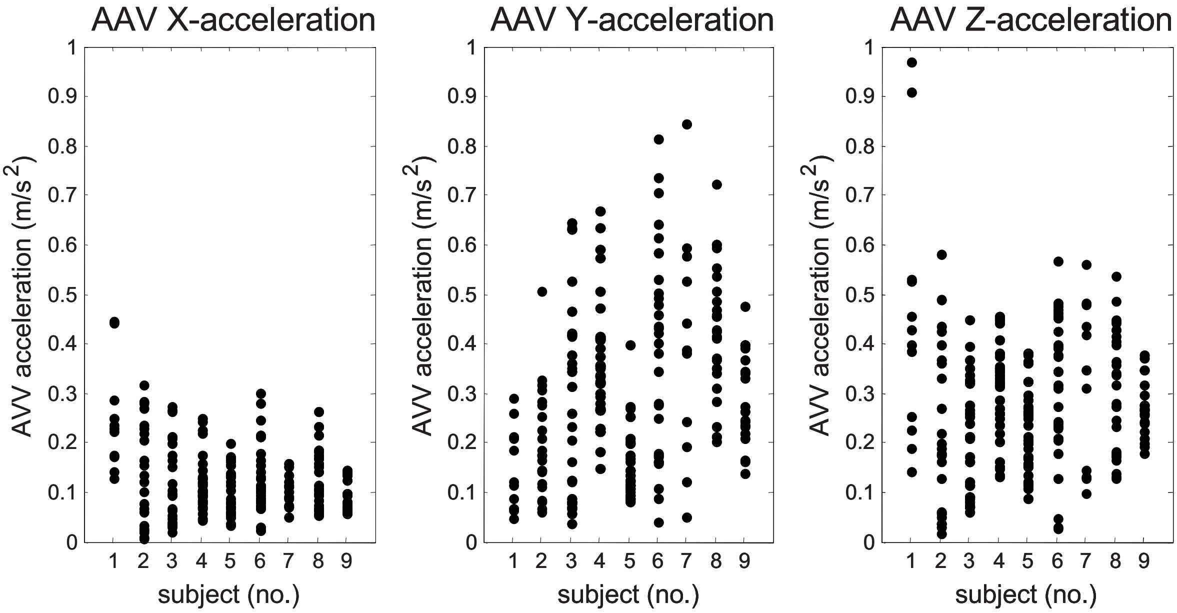

Figure 4-4. *Absolute average values (AAV) for the X-, Y- and Z- ship accelerations shown for all experimental trials per subject.*

Table 4-1. *Results of the GEE regression analysis. At the top of the table the resulting regression model is displayed. For each of the 5 dependent variables, described in the left column, the constants and regression coefficients for the model are displayed, including standard errors and p-values.*

Outcome = Constant	*+ A_1*	*· AAV Y- acceleration*
	+ A_2	*· AAV Z- acceleration*
	+ B	*· Work pace (free = 0, constrained = 1)*
	+ C	*· Task symmetry (symmetric = 0, asymmetric = 1)*

		Coefficient (standard error) for:			
		Ship motion variables		**Task conditions**	
	Constant	**AAV Y-acceleration**	**AAV Z-acceleration**	**Work pace**	**Task symmetry**
Total net moment (Nm)	**327 (19)**	2 (12)	**33(9)**	**5 (2)**	-2 (3)
	(p < 0.001)	(p = 0.863)	(p < 0.001)	(p = 0.001)	(p = 0.427)
Compression force (N)	**4823 (291)**	88 (265)	**917 (248)**	44 (58)	71 (40)
	(p <0.001)	(p = 0.739)	(p < 0.001)	(p = 0.443)	(p = 0.073)
Forward shear force(N)	**1630 (121)**	-68 (47)	148 (140)	13 (19)	21 (20)
	(p < 0.001)	(p =0.147)	(p = 0.292)	(p = 0.482)	(p = 0.299)
Lateral shear force (N)	**146 (38)**	6 (30)	-78 (62)	-4 (6)	14 (11)
	(p < 0.001)	(p = 0.838)	(p = 0.211)	(p = 0.441)	(p = 0.215)
Total ship acceleration at peak net total moment (m/s^2)	**9.59 (0.04)**	**0.22 (0.06)**	**1.10 (0.26)**	0.05 (0.03)	0.01 (0.06)
	(p < 0.001)	(p < 0.001)	(p < 0.001)	(p = 0.099)	(p = 0.837)
Average abdominal EMG (%MVC)	**5.75 (1.03)**	-0.14 (0.65)	0.72 (2.28)	0.68 (0.39)	-0.37 (0.33)
	(p < 0.001)	(p = 0.825)	(p = 0.752)	(p = 0.082)	(p = 0.259)

Significant effects (p < 0.05) are indicated by bold values.

Maximum ship angles during the experiment trials ranged up to about 10°. Figure 4-5 shows the X- and Y-angles of the ship at the instant of peak total net moment for all the subjects, for the experimental trials in which the free work pace lifts were performed. Generally, the rotations around the X-axis were of a higher magnitude than the rotations around the Y-axis. The additional GEE regression analysis revealed that subjects did adjust their body posture to these ship rotations. For every degree of ship rotation, a significant counter rotation of 0.97° (SE 0.03, $p < 0.001$) and 0.72° (SE 0.11, $p < 0.001$) of the body inclination angle was found for the rotation around the X-axis (roll) and Y-axis (pitch) of the ship, respectively. In other words, subjects held their body posture more or less constant with regard to the gravitational vertical.

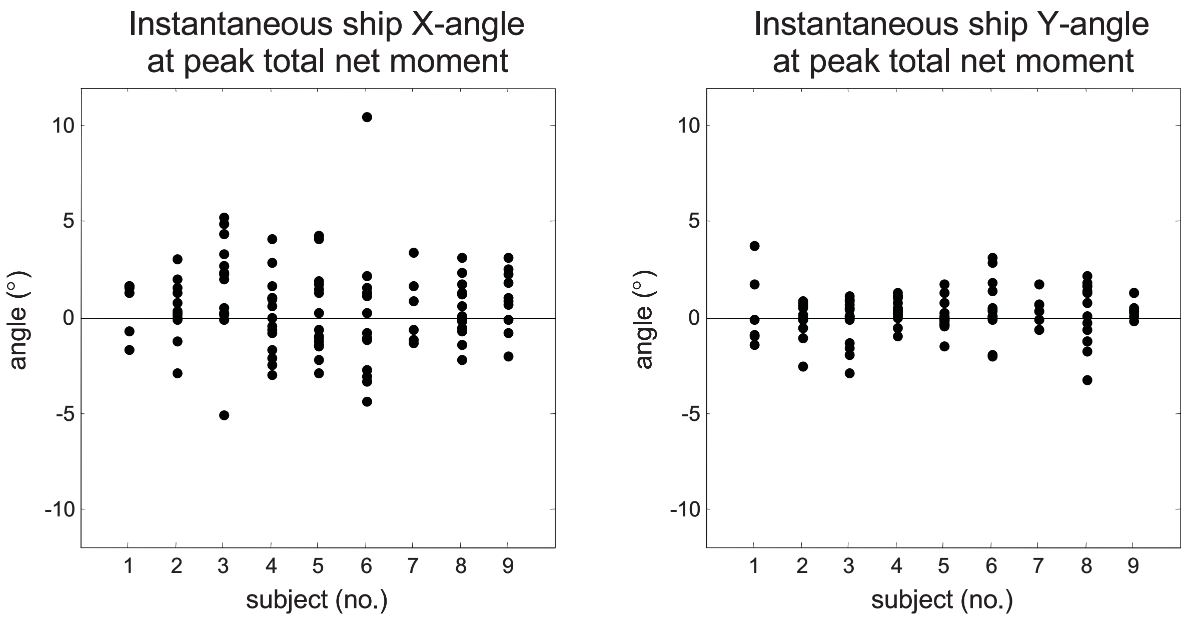

Figure 4-5. *Ship X- and Y- angles at the instant of peak total net moment shown for all experimental trials per subject.*

DISCUSSION

Effect of upward ship acceleration

Both the peak total net moment and the compression force (but not the forward and lateral shear forces) significantly increased as result of an increase in the variation (AAV) of the Z-acceleration of the ship. The peak total net moment increased 10.1% per m/s^2 of AAV Z-acceleration and this can probably be explained by a comparable increase of the instantaneous total ship acceleration at the instant of peak total net moment (11.4%) per m/s^2 of AAV Z-acceleration. Although the effect of the AAV Z-acceleration for the compression force was in the same direction, the magnitude of the effect (19.1% per m/s^2 AAV Z-acceleration) was larger than for the peak total net moment. A possible explanation for this larger effect could be that, with increasing ship motion, subjects try to increase stability of the lumbar spine, by increasing abdominal co-contraction, which has been shown to increase spine compression force (Granata & Marras, 2000). However, abdominal co-contraction was not significantly affected by the AAV of the Z-acceleration. Comparably, Matthews et al. (2007) did not find an effect of simulated ship motion on most of the trunk muscles. Another explanation could be that the recruitment pattern of the back muscles changes with increasing ship motion. It could be, for example, that subjects used more superficial muscles when ship motion increased, which could have resulted in an overestimation of the total muscle force produced by the back muscle, thereby causing an overestimation of the effect of the AAV of the Z-acceleration on the compression force. Other explanations for the difference in magnitude of the effect of the AAV of the Z-acceleration on the total net moment and the compression force can be sought in systematic errors in both biomechanical models that were used. In the EMG-driven trunk muscle model, errors in, for example, the non-linear EMG-force relation could have caused an overestimation of the effect of ship acceleration on muscle forces. Also for the LSM, systematic errors (e.g. camera movement, errors in measurement of ship accelerations) could have altered the effect of the AAV of the Z-acceleration on the net total moment but this is unlikely since the bottom-up and the top-down analysis yielded similar results.

Effect of constraining the work pace

When constraining the work pace, the instantaneous total ship acceleration at the instant of peak moment did not increase. Thus, with unrestricted timing, subjects did not time their lifting movement in such a way that peak moments occurred at instants of small ship accelerations. Also, no significant effect on peak net moments was found for the interaction between AAV of the ship acceleration and work pace. Nevertheless, lifting at a constrained work pace resulted in a marginal

(1.5%) but significant increase in total net moment compared to lifting at the free work pace. This may have been due to subtle changes in lifting pattern.

Effect of sideward ship acceleration

The AAV of the Y-acceleration of the ship did not appear to have an affect on low back loading. This can be understood when realising that the measured Y-acceleration is mainly caused by gravity rather than by sideward motions of the ship. After all, rotation about the longitudinal X-axis (roll) of the ship results in a substantial projection of the gravity vector along the local (sideward) Y-axis of the ship (R^2 = 0.87 between X-angle and Y-acceleration). It appeared that subjects almost completely adjusted their body posture to the orientation of the ship so that overall body posture was held more or less constant with regard to the gravitational vertical. This allowed subjects to keep their body centre of mass projection within the base of support formed by the feet, thereby preventing loss of balance. As a result, the Y-acceleration that was caused by gravity was counteracted by adaptations in the overall body orientation so that low back loading remained unaffected by Y-acceleration.

Effect of asymmetry

In the present study, asymmetry did not significantly affect any of the low back loading variables. This is in contrast with the findings of Marras & Davis (1998) who found an increase in compression force, a decrease in forward shear force and an increase in lateral shear force when the asymmetry of the lift increased. The reason why these effects were not found in the present study could be due to the fact that, except with regard to foot direction, no specific foot placement instruction was given. All subjects used asymmetrical foot placement (because this was more stable), for symmetrical as well as asymmetrical lifting conditions. In the asymmetrical lifts this could have resulted in subjects rotating more towards the load. Therefore, the actual difference in asymmetry of lifting kinematics between symmetric and asymmetric lifting conditions may have been small. In addition, the complex asymmetric 6 degrees of freedom ship motion may have enhanced asymmetrical back loading in both the symmetrical and asymmetrical lifting conditions.

Practical implications

When thinking in terms of lifting guidelines, a relevant question is how much the box mass would have had to be reduced in the experimental trials to counteract the increase in low back loading due to the ship motion. Based on the effect of ship motion found for the total net moment it is possible to make a rough estimation of the required weight reduction. As can be seen from Figure 4-4, the maximum AAVs of the Z-acceleration were around 0.5 m/s^2 for the majority of the subjects. For this magnitude of Z-acceleration the GEE regression equation for the total net moment predicts an increase of about 15 Nm (see Table 4-1). When using a lever arm of the box with regard to the L5-S1 joint of 60 cm (the approximate lever arm that was observed in the present study) and considering only the force on the box due to gravity (neglecting accelerations), a reduction of the box mass of about 2.5 kg would have been required to counteract the 15 Nm increase in total net moment. For the compression force, the required weight reduction would have been about 4.8 kg, since the effect of ship motion was 1.9 times larger for the compression force than for the net moment. Note that when actual box accelerations during the lift are taken into account, the calculations above would show substantially increased numbers for required weight reduction.

Limitations

Some limitations of the present study should be mentioned. First, measurements were done on a relatively small ship (42 m long) which could have resulted in a ship motion pattern that is hard to predict for the subjects involved. Possibly, ship motion on a larger ship is easier to predict. In this case, people can time their lifting movement better so that the effect of ship motion on low back loading can be reduced. Furthermore, only subjects who had experience with working on a ship at sea participated in the experiment. It could be that subjects with less experience have more balance problems when working on a sailing ship and this could result in a larger effect of ship motion on low back loading. It should also be noted that AAV accelerations in the present experiment were below 1 m/s^2 so that results cannot be generalised to higher ship accelerations. In some of the experimental trials, stronger ship motion occurred, but most of these trials were not included in the statistical analysis because subjects were not able to finish the lifting trial because of the risk of falling. However, subjects also stated that, in practice, they would also try to avoid lifting objects under such conditions. A limitation of the ship motion measurement unit as used in the present study was that it did not measure the angular ship motion around the upward Z-axis (yaw) of the ship. However, it is not likely that this has affected the outcomes of this study because the effects of the ship motion around the Z-axis on the total net moment in the experimental trials were probably negligibly small: the moments due to rotational velocity and acceleration around the other axes (roll and pitch) remained below 0.5 Nm and because the ship only sailed straight ahead during the experiment the contribution of the motions around the Z-axis (yaw) on the total net moment is expected to be even smaller. Finally, five lifts were performed in each trial. The estimated effect of ship motion probably would have been higher when more lifts had been performed in each trial, because then there would have been an increasing chance of lifting at an unfavourable moment in time (for example, at the moment of peak upward ship acceleration). Another limitation is that, as a consequence of measuring at sea, equal conditions could not be applied in all subjects. The use of a GEE regression analysis prevented differences between subjects to affect the results only as far as those differences were systematic. If the response to ship motion would be very different between subjects, such difference could have influenced the results through application of unequal sets of conditions. However, the results show that the AAV of the Z-acceleration was the main variable affecting back loading. Figure 4-4 shows that, with exception of two outliers in subject 1 and a reduced range in subject 9, the AAVs of the Z-acceleration were not very different between subjects. Therefore, between-subject differences in responses to ship motion are unlikely to have had a substantial effect on the present results.

CONCLUSION

The present study showed that ship motion does affect low back loading. Specifically, the variation in Z-acceleration did affect low back loading, but variation in Y-acceleration did not. For most subjects, a maximum AAV of the Z-acceleration of about 0.5 m/s^2 was found. For this magnitude of Z-acceleration, the derived GEE regression equations predicted about 5% increase in total net moment and about 9.5% increase in compression force. The reason why the Y-acceleration, which is mainly determined by the X-angle of the ship, did not affect low back loading was the fact that people adjusted their body inclination angle to the ship angles in such a way that it remained more or less constant relative to the gravitational vertical. The present study also showed that subjects did not time their lifting movement in such a way that the effect of ship acceleration on low back loading was reduced. This is in accordance with previous suggestions, based on simulations (Kingma et al., 2003), that load reduction by favourable timing of lifts on a ship would be hard to achieve.

ACKNOWLEDGEMENTS

The authors would like to thank the crew of the Navy vessel “van Kinsbergen” for their assistance during the experiments and the Royal Netherlands Navy for their financial support.