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LOW BACK LOADING DURING LIFTING ON A SHIP.

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The aim of this study was to find out how timing can affect low back loading during lifting on a ship. Accelerations were measured onboard of a frigate at a moderate sea-state. Those accelerations were applied to an inverse dynamic analysis (using a full-body 3D linked segment model) of lifting movements that had been recorded in the laboratory. It was found that ship accelerations up to an RMS level of 0.68 m/s^2 have little influence on the extending and total low back moment. However, twisting moments may, depending on sailing direction, location on the ship, and subject orientation relative to the ship, be increased by over 50 % when the lifting movement is initiated at the wrong instant.

INTRODUCTION

Manual materials handling on a moving platform, like a ship, might be a risk factor for the development of low back pain due to the influence of accelerations on low back loading (Wertheim, 1998). On the other hand, experienced fishermen may take advantage of the accelerations, for instance by lifting an object during a downward acceleration of the ship. However, ship accelerations are not restricted to one direction, but occur in three directions simultaneously. Moreover, the accelerations in the three directions need not be highly correlated. This would make good timing of a lifting movement on a ship quite complicated, because advantageous acceleration in one direction could be offset by disadvantageous acceleration in another direction.

In this study we predicted the effect of ship acceleration on low back loading by applying actual 3-D accelerations of a ship to an (full-body, 3D) inverse dynamic analysis of lifting movements that had been recorded in the laboratory.

The effect of timing was investigated by 'shifting the lifting movements' over the acceleration signals that had been measured onboard of a frigate at two locations and during sailing in two different directions. In addition, the effect of subject orientation (relative to the ship) during the lifting tasks was investigated by rotating the accelerations in the horizontal plane relative to the subject. The aim was to find out how timing and orientation and positioning of the subject on the ship influence low back loading during symmetrical and asymmetrical lifting.

METHODS

Measurement of ship accelerations

Ship accelerations were measured in 3 dimensions onboard of a 120 m frigate of the Royal Netherlands Navy. Accelerations were measured at the front deck as well as at a midship location. Measurements were performed for 30 minutes at a sample rate of 10 Hz, while the ship was sailing with the waves coming in at an angle of 90° or 30° to the left of the forward axis (Table 1).

	RMS X (m/s^2)	RMS Y (m/s^2)	RMS Z (m/s^2)
Front deck, 90°	0.028	0.584	0.294
Front deck , 30°	0.098	0.234	0.483
Mid ship, 90°	0.039	0.530	0.268
Mid ship, 30°	0.127	0.094	0.173

Table 1 RMS accelerations measured on a frigate in forward-backward (X), sideward (Y) and upward-downward (Z) direction, at two locations on the ship in two sailing directions. Those accelerations were applied to an inverse dynamic analysis of the laboratory-measured lifting movements.

Laboratory Experiment

After signing an informed consent, six healthy young males (average ± S.D.: age 24.3 ± 3.3 yrs, weight 77.1 ± 15.2 kg, height 183.5 ± 9.5 cm) participated in the laboratory experiment. The subjects performed two lifting movements with a 428x348x238 mm (width x depth x height) box,

weighing 15 kg. The box was placed either in front of the subject (symmetrical lift) or at an angle of 30° relative to the sagittal plane (asymmetrical lift). Subjects started and ended the lifting movements in symmetrical upright standing posture and used a leg-technique to lift the box.

Ground reaction forces were measure at 200 Hz using a custom-made 1x1 m forceplate. Movements of body segments were measured at 50 Hz using an automated 3D movement registration system (Optotrak), with four arrays of three cameras. Cuffs had been attached to the lower legs, upper legs, pelvis, trunk, upper arms and lower arms. To each cuff, a 100x100 mm metal plate was attached with a double hinge joint. Four LED markers were attached to each metal plate. The hinges allowed positioning the metal plate in such a way that optimal visibility of the markers was guaranteed. A comparable metal plate with hinges was attached to the box for the lifting movements.

Four additional markers (without a cuff) were attached to the head, so that a total of 48 LED markers was used. Marker positions were low pass filtered at a cut-off frequency of 10 Hz and used, together with the recordings of landmark positions, to reconstruct for each body segment, its anatomical axes and the center of mass and joint center locations during the lifting and pulling tasks.

Segment masses and moments of inertia were derived with the aid of anthropometric measurements and regression equations described by McConville et al. (1980). A full-body 3-D linked segment model was used to calculate the body center of mass position during the tasks and to calculate the net moments at the L5/S1 joint in all three planes of motion (Kingma *et al.,* 1996).

Simulated addition of ship accelerations to the lifting tasks

For both lifting tasks a time-window of the same size as the duration of the task was taken from the (3-D) acceleration signal. This time-window of ship accelerations was then applied to the task that had been recorded in the laboratory as described below. Then the time-window was shifted 0.2 seconds to the right and the procedure was repeated, until the time window had been shifted over the 30 minutes of measurements. This was repeated for the 2 locations on the ship the 2 sailing directions and with 4 perpendicular subject orientations.

The ship acceleration was incorporated in the ground reaction force as follows:

$$\mathbf{F}_g' = \mathbf{F}_g + m_b \, \mathbf{a}_s, \qquad\qquad (1)$$

where $\mathbf{F}_g$ is the measured ground reaction force vector in stationary conditions, $\mathbf{F}_g'$ is the modified ground reaction force, $\mathbf{a}_s$ is the ship acceleration vector, m_b is the body and load mass. Since body kinematics relative to the ship were assumed to be the same as under stationary conditions, the moment of the ground reaction force relative to the body center of mass ($\mathbf{M}_{COM}$) was considered unchanged. This moment was calculated according to:

$$\mathbf{M}_{COM} = (\mathbf{r}_g - \mathbf{r}_{COM}) \times \mathbf{F}_g + \mathbf{M}_g, \qquad\qquad (2)$$

Where $\mathbf{r}_g$ is the vector to the point of application of the ground reaction force, $\mathbf{r}_{COM}$ is the vector to the body center of mass and $\mathbf{M}_g$ is the ground reaction moment (which is non-zero around the vertical axis only). Equations (1) and (2) were used to calculate the new point of application of the ground reaction force ($\mathbf{r}_g'$), using:

$$\mathbf{M}_{COM} = (\mathbf{r}_g' - \mathbf{r}_{COM}) \times \mathbf{F}_g' + \mathbf{M}_g. \qquad\qquad (3)$$

Writing equation (3) in components, results in three equations that can be solved for the two unknowns (i.e., for the horizontal components of the modified point of application of the ground reaction force, $r_{g,\mathrm{x}}'$ and $r_{g,y}'$). Furthermore, the ship acceleration ($\mathbf{a}_s$) was added to the (laboratory-recorded) acceleration of each body segment ($\mathbf{a}_i$), to get a valid equation of linear motion:

$$\mathbf{F}_g' = \sum_{i=1}^{p} m_i \, \mathbf{g} + \sum_{i=1}^{p} m_i \, \mathbf{a}_i', \qquad\qquad (4)$$

where $\mathbf{a}_i'$ is the modified acceleration vector of segment i, m_i is the mass of segment i, $\mathbf{g}$ is the gravity vector and p is the number of segments of the whole body.

$\mathbf{F}_g'$ and $\mathbf{a}_i'$ were inserted in an equation of angular motion in the global axis system, to calculate the net moment at the lumbo-sacral joint. Finally, the moments at the L5/S1 joint were projected onto the pelvic axis system to obtain lateral flexing, extending, and twisting moments. The total moment was calculated as the square root of the summed squared moment components. Finally, the cumulative distribution of peak moments and the number of trials deviating more than 10% from the original moment, were calculated.

RESULTS

First, trials were removed where the projection of the body center of mass would, for 20 ms or more, be outside the support plane, as defined by lines through the heels and

second toe of both feet. The reason to remove these trials was that subjects would have had to adapt their movement pattern to prevent falling. So the current analysis would not be valid. As can be seen from the top of the cumulative distribution of trials (Figures 1-3), less than 10% of the trials had to be removed for the mid ship location and up to almost half of the trials had to be removed for lifting asymmetrically at the front deck. For symmetrical lifting, a more than 10% (31.1 Nm) change of the extending moment was found in less than 1.1% of the simulated lifting trials. For asymmetrical lifting, a 10% (28.8 Nm) change of the extending moment was found in less than 3.1% of the simulated trials. For both lifts, this held for any of the locations on the ship, sailing directions or subject orientations.
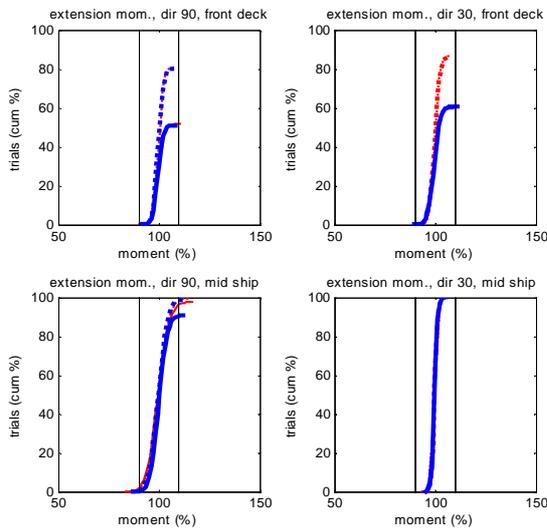

Figure 1. Cumulative distribution of extending moments in simulated application of ship accelerations to asymmetrical lifting movements. Wave angle and location on the ship are indicated in graph titles. Lifting was simulated with the feet pointing forward (dotted, thin line), backward (solid, thin line), to the right (dotted, thick line) or to the left (solid, thick line). Vertical lines indicate 10 % deviation from original moments.

Lateral flexing and twisting moments will only be described for the simulated asymmetrical lift. More than 10% (3.4 Nm) deviation of the lateral flexing moment was found in less than 1% up to over 20% of the simulated trials, dependent on sailing direction, location on the ship and subject orientation. When the waves come in at an angle of 90°, deviations of the lateral flexing moment are especially

dependent on the orientation of the subject (i.e., being large when the subject is standing with the feet pointing forward or backward), and not on the location at the ship (Figure 2). When the waves are coming in at an angle of 30°, deviations of the lateral flexing moment are especially dependent on the location of the ship (being large at the front deck and small at the midship location), and to a lesser extent on the orientation of the subject.
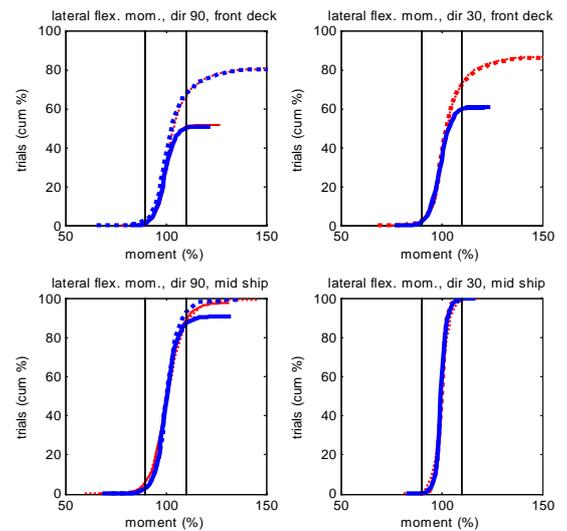

Figure 2. Cumulative distribution of lateral flexing moments in simulated application of ship accelerations to asymmetrical lifting movements. See Figure 1 for an explanation of the graphs.

Twisting moments are more affected by ship accelerations than lateral flexing and extending moments. In asymmetrical lifting, when the waves are coming in at an angle of 90°, a more than 10% (4.5 Nm) change of twisting moments is found in over 60% of the simulated trial at both locations on the ship when subjects would be standing with their feet pointing either forward or backward, and in 20-25% of the simulated trials when subjects are standing with their feet pointing sideward (Figure 3). When the waves are coming in at an angle of 30° a more than 10% change of the twisting moment is found in 10-52% of the simulated trials (dependent on subject orientation) when lifting at the front deck, and in 3-20% of the trials (dependent on subject orientation) when lifting at the midship location. A more than 50% (22.4 Nm) change of the twisting moment is only found in a substantial (2-4%) number of trials when the waves are coming in at an angle of 30° and the subjects are standing with their feet pointing forward or backward
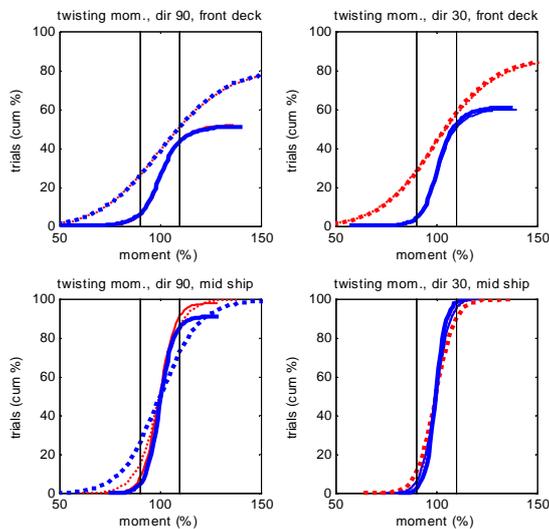
(Figure 3).

Figure 3. Cumulative distribution of *twisting moments in simulated application of ship accelerations to asymmetrical lifting movements. See Figure 1 for an explanation of the graphs.*

DISCUSSION

The current study showed that, up to the acceleration levels used in this simulation, only small changes of the extending and total moment are to be expected, at least when lifting movements are not adapted to accelerations when lifting on a ship. This implies that compression forces at the lumbar spine are not to be expected to be strongly influenced by those accelerations (van Dieën and Kingma, 1999), unless the level of co-contraction is different from a stationary environment. An increased oxygen consumption has been found during a static weight-holding task on a ship compared to a stationary environment (Törner *et al.,* 1988), which suggests that an increased level of co-contraction may actually occur on a ship.

From the current results, the twisting moments seem to be the major point of concern. A substantial number of lifting movements was predicted to result in moments that were 50% higher than in stationary conditions (i.e., 66.2 Nm). Those moments are close to the maximum twisting moments that people can produce (Parnianpour *et al.,* 1988). Epidemiological research suggests that twisting movements are a separate risk factor for the occurrence of low back pain (Hoogendoorn *et al.,* 2000). The twisting moments are likely to increase further when the load mass increases or when the lifting movement becomes more asymmetrical (Kingma *et al.,* 1998).

Evidently, higher ship accelerations would lead to stronger deviations from stationary moments. However, those accelerations would also necessarily lead to adaptation of the movement pattern to prevent falling. Therefore, the current method to predict low back loading would not be valid.

From the perspective of designing tasks on a ship, the current results suggest that, the midship location is better than the front deck, since, deviations of more than 10 % from the peak moments at a stationary surface, were predicted in a lower number of trials, for all subject orientations and both sailing directions. With respect to the orientation of the subject, the results suggest that sideward orientation of the feet is preferable, because the twisting moments deviate less from stationary conditions. However, it should also be noted that adaptation of the movement pattern is more often required when the feet are pointing sideward, and the consequence of such adaptations for low back loading are yet to be investigated.

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