Energy cost associated with moving platforms

Carolyn A Duncan ¹, Scott N Mackinnon ², Jacques F Marais ³, Fabien A Basset Corresp. ³

¹ Graduate School of Industrial and Systems and Engineering, West Virginia University Institute of Technology, Blacksburg, VA, United States
² Division of Maritime Studies, Chalmers University of Technology, Gothenburg, Sweden
³ School of Human Kinetics and Recreation, Memorial University of Newfoundland, St. John’s, NL, Canada

Corresponding Author: Fabien A Basset
Email address: fbasset@mun.ca

Background: Previous research suggests motion induced fatigue (MIF) contributes to significant performance degradation and is likely related to a higher incidence of accidents and injuries. However, the exact effect of continuous multidirectional platform perturbations on energy cost with experienced personnel on boats and other seafaring vessels remains unknown. Objective: The objective of this experiment was to measure the metabolic energy costs (EC) associated with maintaining postural stability in a motion-rich environment. Methods: Twenty volunteer participants, who were free of any musculoskeletal or balance disorders, performed three tasks while immersed in a moving environment that varied motion profiles similar to those experienced by workers on a mid-size commercial fishing vessel [static platform (baseline), low and high motions]. Cardiorespiratory parameters were collected using an indirect calorimetric system that continuously measured breath-by-breath samples. Heart rate was recoded using a wireless heart monitor. Results: Results indicate a systematic increase in metabolic costs associated with increased platform motions. The increases were most pronounced during the standing and lifting activities and were 50% greater during the high motion condition when compared to no motion. Increased heart rates were also observed. Discussion: Platform motions have a significant impact on metabolic costs that are both task and magnitude of motion dependent. Practitioners must take into consideration the influence of motion rich environments upon the systematic accumulation of operator fatigue.
ENERGY COSTS ASSOCIATED WITH MOVING PLATFORMS

Carolyn A. Duncan¹, Scott N. MacKinnon², Jacques F. Marais³, Fabian A. Basset³

¹Graduate School of Industrial and Systems and Engineering, Virginia Tech, Blacksburg, VA, USA
²Division of Maritime Studies, Chalmers University of Technology, Gothenburg, Sweden
³School of Human Kinetics and Recreation, Memorial University of Newfoundland, St. John’s, NL, Canada

Corresponding Author:

Fabien A. Basset, PhD

Address: School of Human Kinetics and Recreation
Memorial University of Newfoundland
St. John's, NL, CANADA, A1C 5S7
Telephone: (709) 864-6132
Email: fbasset@mun.ca
Abstract

Background: Previous research suggests motion induced fatigue contributes to significant performance degradation and is likely related to a higher incidence of accidents and injuries. However, the exact effect of continuous multidirectional platform perturbations on energy cost with experienced personnel on boats and other seafaring vessels remains unknown.

Objective: The objective of this experiment was to measure the metabolic energy costs associated with maintaining postural stability in a motion-rich environment.

Methods: Twenty volunteer participants, who were free of any musculoskeletal or balance disorders, performed three tasks while immersed in a moving environment that varied motion profiles similar to those experienced by workers on a mid-size commercial fishing vessel (static platform (baseline), low and high motions). Measures of ventilation were collected using a portable metabolic system that continuously measured breath-by-breath samples and heart rate using a wireless heart monitor.

Results: Results indicate a systematic increase in metabolic costs associated with increased platform motions. The increases were most pronounced during the standing and lifting activities and were 50% greater during the high motion condition when compared to no motion. Increased heart rates were also observed.

Discussion: Platform motions have a significant impact on metabolic costs that are both task and magnitude of motion dependent. Practitioners must take into consideration the influence of motion rich environments upon the systematic accumulation of operator fatigue.
ABBREVIATIONS:

BoS: base of support
CoM: centre of mass
HM: high motion
LM: low motion
MII: motion induced interruption
MMH: manual materials handling
NM: no motion
RER: respiratory exchange ratio
RMR: resting metabolic rate
Introduction

Motion-rich environments may have effects on the human body that can adversely impact biomechanical, physiological and psychological aspects of vocational performance (Crossland and Lloyd, 1993; Crossland, 1994; Wertheim, 1998; Duncan et al., 2010; Duncan et al., 2012). More specifically, platform motions can negatively impact upon an operator’s ability to manage command, control and communication systems, carry out navigational tasks, perform normal ship operation and maintenance functions and prepare food in maritime industries that involve moving platforms including but not limited to coast guard, maritime shipping and the offshore petroleum industry (Dobie, 2003). While the strenuous and dangerous nature of many offshore occupations is obvious, wave induced platform motions are likely responsible for accidents and injuries associated with reduced postural stability and increased work-related energy costs (Wertheim, 1998).

Effects on performance have been related to magnitude and frequency of the platform motions (Colwell, 1989; Bles et al, 1998; Wertheim, 1998; MacKinnon et al, 2011 Duncan et al., 2014). Continuous exposure to motion-rich environments makes performing tasks more difficult because of the continuous postural adjustments needed to maintain balance (Duncan et al, 2007). These required postural adjustments will add to the energy cost compared to work done in a stable environment (Baitis et al, 1995; Wertheim, 1998). This increased energy cost may be related to motion induced fatigue (MIF). MIF has been shown to increase injury occurrences and decrease productivity in offshore workers (Colwell, 1989; Haward et al, 2009). To the authors’ knowledge current research on MIF fatigue is limited. It has been suggested MIF can be broadly characterized into two categories: fatigue due to loss or poor quality of sleep and the added
energy costs associated with doing work in a moving environment. Unlike motion induced
sickness, crew members are unable to habituate to the effects of MIF, likely resulting in
accumulative effects leading to crew ineffectiveness such as lack or loss of situation awareness
and errors in judgment (Stevens and Parsons, 2002). Accumulated fatigue can also impact upon
the ability and quality of performing manual materials handling (MMH) activities in a safe and
efficient manner. A better understanding of the impact of increased energy cost in moving
environments may provide insight into the design and execution of tasks performed in maritime
environments and lead to a reduction of risk of errors and injuries and improvements in safety
and performance.

Accidents and injuries at sea often identify operator fatigue as the contributing cause, however,
little research to date has attempted to quantify the relationship between platform motion
magnitude and operator energy cost. Wertheim (1998) reported a series of earlier studies that
measured energy cost via indirect calorimetry technique in a moving environment. All of these
were done under controlled conditions within a ship motion simulator facility. A variety of
activities, including standing, treadmill running, and crate stacking were examined. Results
showed increases in oxygen uptake of 7% compared to no motion condition during the simulated
ship movements although the increases were less than expected. Whether self-reported or
observed by investigators, participants consistently reported being "severely" fatigued following
testing. While a holistic approach to studying any problem is desirable, it is recognized that
focused research on the mechanisms underlying MIF physiological responses is required. By
addressing this knowledge gap, it is expected that such research will improve upon the
understanding of the direct and indirect effects of MIF on human performance in moving

The purpose of this study was to quantify the additional energy required by persons performing
common tasks in simulated maritime environments as compared to stable (i.e. land)
environments. It is hypothesized that the continuous multi-directional perturbations will
significantly increase the energy costs associated with performing sitting, standing and manual
materials handling tasks.

Materials & Methods

Participants

Twenty (10 males, 10 females) (age: 23.4±2.0 years; mass: 74.5±13.1 kg; stature: 172±7.0 cm;
BMI: 25.1±4.8 kg m\(^{-2}\)) participants were recruited for this study. Participants reported no
susceptibility to motion sickness and were free of balance disorders and musculoskeletal diseases
or injuries. Due to the influence of experience on habituation and postural control (Duncan et al.,
In Press) only individuals with no experience working in maritime environments were eligible
for this study. Ethical approval for this experiment was given by the Memorial University of
Newfoundland’s Human Investigations Committee. All participants have signed the consent
form prior to undergoing any physical tests.

Procedures

Participants performed sitting, standing and lifting/lowering tasks while being exposed to three
motion conditions (no motion, low motion, high motion). The experimental protocol was
completed over three sessions with at least twenty-four hours between each session to ensure for
sufficient recovery and to reduce the effects of accumulative fatigue. Each session required the
participant to perform a task (i.e. quiet sitting on a chair, standing in an upright position, or
lifting and lowering a load) for each of the three motion conditions. Each session began with
quiet sitting while resting metabolic rate (RMR) was collected. Exposure to each motion
condition lasted ten minutes with a minimum of a five-minute rest period between conditions.
While every attempt was made to randomize the task order presentation of the motion, one
concession was made: the no motion trial was always presented to the participant first. The no
motion trial was considered to be a baseline condition from which all other data collection
sessions could be compared or perhaps could serve as a normalizing value. Subsequently, the
low or high motion trial was randomly presented so all participants got both high and low motion
conditions (Figure 1). Participants were instructed to refrain from smoking and any physical
activity or consume food or drink (except water) three hours prior to testing (Compher et al,
2006).

Experimental Tasks

Participants required to sit on a chair (seat width: 0.48 m; seat depth: 0.48 m; seat height: 0.42 m;
armrest height: 0.64 m; backrest height: 0.77 m) firmly situated to the platform with front legs in
the middle of the platform facing the “bow” (front) direction for all trials. Throughout the task
the participants were instructed to keep their torsos against the backrest, arms on the arm rests,
and legs uncrossed with feet placed flat on the ground.
During standing trials participants remained in the middle of the motion platform in an erect standing position with arms along their sides, feet approximately shoulder width apart, weight evenly distributed between their feet and facing the bow of the platform (Figure 2). Stepping was permitted to correct for balance interruptions during the motion trials. Upon stepping participants were instructed to return to the original foot positions as soon as balance has been regained.

A bimanual sagittal plane lifting/lowering task required participants to lift and lower a 5.0 kg load (length: 0.327 m; width: 0.327 m, height: 0.270 m) directly to and from a table (width: 1.54 m, depth: 0.52 m; height from floor: 0.72 m) securely situated 0.60 m directly in front of the participant facing the bow direction (Figure 3). Load size and lift dimensions were determined from the revised NIOSH lifting equation for safe lifting (Waters et al., 1993). Throughout the task participants were required to keep their feet shoulder width apart and parallel to the table. Lifts and lowers were separated by ten second intervals. The start of each lift or lower were initiated via audible signals and were performed consecutively at a rate of three lifts per minute and three lowers per minute resulting in a cumulative task rate of six manipulations per minute for a total of 60 MMH events for each condition. Participant used their own preferred lifting and lowering technique.
Experimental Apparatus

All motion conditions were performed on a Moog 6DOF2000E electric motion platform. The platform consisted of a 2 by 2 m metal platform with 1.02 m high railings along the perimeter. A canopy enclosure eliminated external horizontal and vertical cues from the participant’s field of vision. Motion conditions varied in amplitude and frequency and were derived from captured wave induced ship motions using linear wave theory that allowed for the profile to vary in magnitude (Lloyd, 1993). Five degrees of freedom were used (roll, pitch, heave, surge, sway) (Figure 4). Linear equations used to develop all motion profiles are detailed (Equations 1-5). The low motion (LM) profile reflected a 10% increase in motion frequency relative to the original vessel from which the motion profiles were recorded and the high motion (HM) profile was characterized by a 15% increase in frequency and a 265% increase in amplitude relative to the seagoing motion profile (Table 1). Statistical analysis of differences between these conditions, performed using students’ t-tests, confirm that the RMS of the LM and HM conditions were significantly difference in pitch and roll directions ($p<0.001$). These conditions were compared to a stable, no motion condition (NM).

\[
\begin{align*}
\text{Roll (x) (deg/s/s)} &= 0.8(\sin(1.050t) + 1.25\sin(0.11t + 0.05)) \\
\text{Pitch (y) (deg/s/s)} &= 0.8(2.5\sin(1.76t + 0.5) + \sin(t) – 1.5) \\
\text{Heave (G)} &= 0.1(5\sin(1.595t + 2) + 15\sin(1.21t)) \\
\text{Surge (G)} &= 0.1(7.8\sin(0.649t + 4.8) + 7.8\sin(0.825t + 3.8) + 0.5) \\
\text{Sway (G)} &= 0.1(18\sin(0.583t + 5) + 9\sin(1.122t + 5.4) – 0.25)
\end{align*}
\]

Eq. 1  Eq. 2  Eq. 3  Eq. 4  Eq. 5
Physiological Measurements

Oxygen uptake (VO₂), carbon dioxide output (VCO₂), breathing frequency (fₐ) and tidal volume (Vₜ) were continuously collected by an automated breath-by-breath system (Sensor Medics® version Vmax ST 1.0) using a Nafion filter tube and a turbine flow meter (opto-electric).

Respiratory exchange ratio (RER) and minute ventilation (VE) were calculated as the quotient of VCO₂ on VO₂ and the product of fₐ and Vₜ, respectively. Heart rate values were telemetered via a Polar heart rate monitor (PolarElectro, Kempele, Finland) and recorded online. Prior to testing, gas analyzers and volume were calibrated with certified calibration gases (16.0% O₂ and 3.98% CO₂) and with a 3-liter calibration syringe, respectively.

Data Reduction

The RMR data were truncated by 10 minutes out of 20 minutes of data collection. This procedure discarded the first and last 5 minutes to nullify any metabolic rate fluctuation due to familiarization with the facemask and the expectations related to the termination of data collection. The metabolic data for sitting, standing, and lifting were truncated by 2 minutes out of 10 minutes data collection to account for the metabolic inertia and depression at the beginning and at the end data collection, respectively. The remaining segments (10 minutes for RMR and 8 minutes for the experimental conditions) were integrated and normalized over time. Oxygen uptake values were converted and expressed as energy cost in metabolic equivalent (MET). The same truncation and integration procedures were applied to the heart rate data. This data
reduction process was undertaken to produce stable metabolic steady state information for subsequent statistical analyses. Energy cost was computed using the following equation:

\[
\text{Energy cost (MET)} = \frac{\dot{V}O_2 (\text{ml min}^{-1} \text{kg}^{-1})}{1 \text{ MET (3.5 ml min}^{-1} \text{kg}^{-1})}
\]

Eq.6

Statistical Analyses

Differences between baseline, rest periods, and tasks were analyzed using repeated measures analyses of co-variance (ANCOVA) with gender (2 levels: male and female) entered as a co-variate. Post-hoc comparisons were performed using Bonferroni corrected t-tests to decompose significant interaction and/or main significant effects. Assumptions of sphericity were also investigated using Mauchley’s test and the adjusted Greenhouse-Geisser correction factor (epsilon (\(\epsilon\)) was used to identify significance (\(p \leq 0.05\)) if sphericity was violated). Prior to each statistical analysis, normality and homogeneity of data sets were verified via Kolmogorov-Smirnov tests and Levene’s tests respectively. All statistical analyses were performed using Statistical Package for Social Sciences (version 21.0) (SIBM Corp., Armonk, NY, USA).

Results

Energy Cost

Results of the repeated measures ANCOVA indicated no significant differences in energy cost at the beginning of each trial (\(p \geq 0.05\)) suggesting participants started each trial with similar energy cost. The interaction effect between motion and gender was also not significant. Analysis of energy cost post-exposure revealed no significant differences in the interaction effect between motion and gender for any task or motion condition (\(p \geq 0.05\)). Significant differences in the main effect of motion between all conditions and all tasks (Sit: \(F(1.88,0.35) = 47.67, p<0.001; d=0.716, 95\%\text{CI}= -0.255, -0.093\); Stand: \(F(1.08,26.65) = 59.16, p<0.001; d=0.779, 95\%\text{CI}= -1.353, -0.640\);
Lift: \( F(1.24, 18.89) = 80.67, p<0.001; d=0.925, 95\%CI= -1.155, -0.509 \) (Figure 5; panel A).

Significant differences in energy cost were also found between NM and LM conditions but only for the standing and lifting task.

Table 2 displays the secondary cardio-respiratory outputs (\( \dot{V}CO_2 \), \( \dot{V}E \), \( V_T \), \( f_R \) and RER) as additional information; however, no statistical analyses were performed owing to the limited relevance of these parameters to the research question.

Heart Rate

Examination of the interaction effect between gender and heart rate was not statistically significant for any task (\( p \geq 0.05 \)). Evaluation of the main effect of motion revealed statistically significant differences for standing (\( F(1.27, 759.48) = 10.14, p<0.01; d=0.348, 95\%CI= -1.728, -0.806 \)) and lifting (\( F(1.35, 2274.93) = 23.10, p<0.001; d=0.549, 95\%CI= -1.353, -0.640 \)) but not sitting (\( F(1.65, 610) = 0.50, p=0.58; d=0.026, 95\%CI= -0.279, -0.041 \)) (Figure 5; panel B). Post hoc comparisons reveal standing in LM heart rate was significantly lower than NM (\( p=0.007; 95\%CI= -0.664, -0.301 \)) and HM (\( p<0.001; 95\%CI= -2.242, -0.896 \)). Lifting heart rate during the HM condition was significantly greater than both NM (\( p<0.001; 95\%CI= -2.196, -1.040 \)) and LM (\( p<0.001; 95\%CI= -1.770, -0.716 \)).
Discussion

Work in moving environments is perceived to be much harder than performing similar tasks in stable environments. When working in moving environments fatigue can be caused by a number of different factors including motion induced sickness (or perhaps the medications used to mediate the effects of motion sickness), motion induced loss of sleep and motion induced interruptions (due to the increased muscular effort needed to maintain postural stability (Dobbins et al., 2008). However, little research has examined the fatigue related to the direct energy cost due to motion-rich environments.

The use of simulated motion environments (Colwell, 2005) has provided researchers with a controlled setting in which to assess human responses to motion environments and allows for more controlled counterbalanced experimental designs compared to research “at sea”. While research undertaken during sea trials have an element of ecological validity, a major limitation is reproducibility and control of under-foot motions between experimental conditions. Developing accurate performance prediction models require that experimental protocols avail of systematic controls of motion-defining parameters (i.e. frequency, amplitude). The simulated motions employed in this experiment were derived from sea trials and can be deemed typical of those a mariner would experience, particularly on a small near-shore vessel. It was decided to increase the frequency and/or amplitude profiles to increase the demands upon the participant, specifically to create a distinction between the low and high motion conditions as described in Table 1 (linear accelerations and angular velocities). Previous studies employed similar motion characteristics as this experiment’s LM profile and reflected rather calm sea conditions (Dobie and May, 2002; Heus et al, 1998; Wertheim et al, 2002). The HM profile in this experiment
reflects a somewhat higher sea state, with maximal linear accelerations and angular velocities at least twice the magnitude of the LM profile. Roll and pitch parameters are of particular interest since these types of motions have been shown to (independently or in combination) have the greatest effect on MIIs and energy cost (Wertheim et al., 1994). Maximum HM roll and pitch components were 141% and 191% larger than the LM condition’s, respectively, therefore, showing that an increase in the magnitude of the sea-state will result in increased energy cost. These profiles are likely more reflective of larger vessel and more deep-sea locations.

Results of this study indicate that seafarers may have significantly increased energy cost due to working in motion-rich environments. Thus, long-term exposure to motion-rich environments will likely have a cumulative fatigue effect that can potentially lead to increased risk of falls, musculoskeletal injury, and human error. This is especially problematic in the marine context since workers can be exposed to vessel motions for extended periods of time, increasing the risk of the negative effects of motion-induced fatigue (Baitis et al., 1995; Colwell, 1989). The focus of this paper was to quantify energy cost of persons performing three common tasks (sitting, standing and MMH) during three different motion conditions. Results indicate significant differences in energy cost between all motion conditions for nearly all tasks (all motion conditions were significantly greater than NM while HM was significantly greater than LM). Findings show that as motion intensity increases, so does energy demand and these outcomes fit with previous examinations of O₂ uptake and energy cost in moving environments (Heus et al., 1998; Wertheim et al., 2002; Breidahl et al., 2013). However, others have reported that walking on a laterally oscillating platform can reduce energy cost of walking (Joshi V et al. 2015). These outcomes tend to show that humans may not be able to entrain to it. Nevertheless, the current
article operates far from such entrainment regimes, thereby generally resulting in increased energy cost. In other words, there should not always be an increase in energy costs on a moving platform.

While statistical analyses between tasks (i.e. sitting, standing and MMH) may be of interest, intuitively it is understood there will be differences in selected tasks’ workload demands. Energy requirements will increase proportionately with increased workload (Astrand and Rodahl, 1986). Comparing the three tasks, energy requirements were lowest for the sitting task, followed by standing, and highest for lifting/lowering (see Figure 3, panel A). This seems reasonable given the potential increased instability of upright bipedal stance compared with sitting in a chair with back support.

NM sitting energy cost values were comparable to previous studies (Astrand and Rodahl, 1986; Levine et al, 2000). There was a significant (25%) increase in the HM sitting energy cost and a significant (5%) increase in the LM sitting condition. These differences were considerably less than the standing and lifting tasks. These findings seem reasonable because during sitting the participant’s CoM likely remains over the base of support, predominantly defined by the area of the seat pan and foot positions on the floor (i.e. larger base of support). No correction for loss of balance are required and it is likely that the majority of any additional muscular activation relates to trunk stabilization and may primarily be related to only head/upper torso stabilization. Sitting energy cost may be most affected by motions involving increased forward pitch velocities since operators can rely on the backrest for high backward pitch moments. Roll motions would have a lesser effect on energy demands if arm rests are present since arm stabilization will mediate side-
to-side movements. Even though relatively small sitting energy cost changes were observed across motions conditions, long-term exposure to motions could still induce a fatiguing effect.

NM standing energy cost was also consistent with previous findings (Garg et al, 1978; Houdijk et al, 2009; Pandolf et al, 1977; Levine et al, 2000). Differences in NM energy cost were much more apparent during standing trials, with increases of 34.7% and 157.7% for LM and HM conditions, respectively. Unlike sitting, standing creates situations for reduced postural stability and thus greater mechanical demands upon the operator. While standing in motion rich environments workers are exposed to greater motion-induced moments of inertia that directly influence an operator’s ability to maintain the centre of mass (COM) within BoS limits. When the CoM reaches or exceeds the functional stability limits, balance is compromised, and operators have no option other than employing postural adjustments to correct for balance perturbations (Winter, 1995). Standing in high motion states will require the operator to continually react and correct for perturbations. Previous work by Duncan et al. (2007) has found that as platform perturbation magnitudes increase so do the number of stepping strategies that are used to maintain balance. This increasing magnitude of postural responses would require greater energy cost due to the increased muscular contractions required to move the limbs. Additionally, when not stepping to regain balance, the muscular contractions required to produce a moment to keep the CoM within the BoS to retain balance in response to larger perturbations would also be greater, and thus, requiring a higher energy cost.

Interestingly, the impact of motion on heart rate and energy cost was different. While significant changes in energy cost were displayed for all tasks, only the lifting task displayed a similar
increasing trend with increased motion, while heart rate during LM was significantly less than both high and no motion conditions. This is unlike previous findings (Heus et al., 1998) that found the energy costs were accompanied by increases in heart rate; however, in their study only one motion condition was measured in both seas and simulated ocean conditions. It is plausible that during LM positive inotropic agents (e.g., catecholamines) increased ventricular contraction and, therefore, systolic ejection volume to maintain tissue oxygen perfusion at the cellular-capillary level. Future research is needed to confirm these hypotheses.

While this study examined only two motions in comparison to a baseline (no motion) condition, future work should examine a broad spectrum of motions described by systematic changes in frequency and amplitude in all 6 degrees of freedom. Such an experimental approach will allow for regression analyses to be used to describe platform motions and task-specific energy cost. Increased energy cost likely results in increased fatigue of the maritime worker, and in turn, may cause decreased ability to perform work effectively (or safely). Additionally, general fatigue may result in decreased morale of workers as the effects of motion-induced fatigue are typically considered a negative subjective experience (Fu et al., 2001; Shen et al., 2006). Acute and chronic fatigue appears to be dependent on a number of factors specific to a seafaring occupation including tour length, environmental factors, extended shift length and switching from sea to port with fatigue appearing to increase at the end of tours (Wadsworth, 2006; Wadsworth et al., 2008). This may lead to increased risk of injuries and errors that could lead to further accidents and injuries.
More research effort must focus on the mechanisms and outcomes of motion-induced fatigue. A better understanding of motion-induced fatigue will allow for improved planning of work for persons at sea for extended periods of time. While this study demonstrated increases in energy cost over a short period of time, this may or may not reflect extended exposure time responses.

Defining the relationship between platform motions and task-specific energy demands will contribute to developing guidance notes and strategies regarding habitability, work-rest ratios and shift work scheduling, accidents and injuries, crewing and crew satisfaction, nutrition demands and workstation and vessel design.

Ergonomic Application.

Ergonomists and human factors engineers must consider these increased energy costs when evaluating occupational demands of seafarers. Workers in moving environments require more energy to perform equivalent tasks to those working in non-moving environments. Therefore, manual materials handling guidelines, for example, must be sensitive to the environment the task occurs. For example, currently the NIOSH lifting equation, assuming the baseline maximum aerobic capacity of U.S. workers is 9.5 kcal min\(^{-1}\) (aerobic lifting capacity of an average 40-year old female worker), workers should be lifting at no more than 50% of their maximum (4.75 kcal min\(^{-1}\)) for 1 hour or less, 40% of their maximum (3.8 kcal min\(^{-1}\)) for 1-2 hours; and 33% of their maximum (3.1 kcal min\(^{-1}\)) for 2-8 hours (Waters et al., 1993). Conversion of the results of this study to kcal min\(^{-1}\) has found that during the LM and HM condition the energy cost is 3.78 and 5.33 kcal min\(^{-1}\), respectively. Therefore, changes to the lifting task would have to be made in order to make it safe for workers performing this same task in a moving environment. Based on the increases in energy cost during the standing and holding tasks, more conservative estimates would also need to be applied to all MMH tasks, including pulling pushing and carrying.
Conclusions

This research reflects attempts to develop an experimental protocol to assess the effects of motion on the energy demands of persons working in motion-rich environments.

From the results, it can be concluded:

1. **Energy cost** of common manual materials handling tasks are greater in moving environments when compared to non-moving environments.

2. **Energy cost** demands are dependent upon the magnitude of the platform perturbations and the nature of the task being performed, with tasks that involve the stabilization of upright stance having higher energy demands.

3. These results provide **objective outcomes on energy cost of commonly performed tasks** by workers in maritime environments.

4. Ergonomists and human factors professionals could implement strategies based on the study outcomes to mitigate motion-induced fatigue with the aim to maintain operator performance, minimize human factors errors, and reduce work-related injuries.

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Table 1 (on next page)

Motion profile characteristics including maximum, minimum and root mean square of each degree of freedom for low and high motion conditions.
Table 1: Motion profile characteristics including maximum, minimum and root mean square of each degree of freedom for low and high motion conditions.

| Degree of Freedom | Low Motion | High Motion |          |          |          |
|-------------------|------------|-------------|----------|----------|----------|
|                   | RMS       | Max.        | Min.     | RMS      | Max.     | Min.     |
| Sway (g)          | 0.11      | 0.22        | -0.22    | 0.12     | 0.24     | -0.24    |
| Surge (g)         | 0.23      | 0.44        | -0.44    | 0.25     | 0.48     | -0.48    |
| Heave (g)         | 0.24      | 0.43        | 0.00     | 0.26     | 0.47     | 0.00     |
| Pitch (deg/s/s)   | 3.74      | 5.30        | -5.30    | 10.24    | 14.51    | -14.50   |
| Roll (deg/s/s)    | 4.42      | 6.99        | -6.99    | 11.97    | 16.97    | -16.97   |
| Yaw (deg/s/s)     | 0.00      | 0.00        | 0.00     | 0.00     | 0.00     | 0.00     |
Table 2 (on next page)

Cardiorespiratory parameters recoded during the experimental sessions with the indirect calorimetry system.

Mean (SD)
**Table 2**: Cardiorespiratory parameters recoded during the experimental sessions with the indirect calorimetry system

|       | SIT                |           | STAND               |           | LIFT                |           |
|-------|--------------------|-----------|---------------------|-----------|---------------------|-----------|
|       | NM | LM | HM | NM | LM | HM | NM | LM | HM | NM | LM | HM |
| \(\text{VO}_2\) (L min\(^{-1}\)) | 0.201 | 0.212 | 0.254 | 0.256 | 0.352 | 0.666 | 0.690 | 0.757 | 1.066 |
|       | (0.05) | (0.04) | (0.06) | (0.07) | (0.11) | (0.26) | (0.11) | (0.17) | (0.29) |
| \(\text{VCO}_2\) (L min\(^{-1}\)) | 0.180 | 0.187 | 0.231 | 0.217 | 0.299 | 0.595 | 0.617 | 0.667 | 0.993 |
|       | (0.050) | (0.042) | (0.060) | (0.050) | (0.083) | (0.244) | (0.102) | (0.148) | (0.303) |
| RER (AU) | 0.89 | 0.88 | 0.91 | 0.86 | 0.86 | 0.89 | 0.90 | 0.88 | 0.93 |
|       | (0.07) | (0.07) | (0.07) | (0.08) | (0.08) | (0.09) | (0.06) | (0.05) | (0.07) |
| VE (L min\(^{-1}\)) | 7.1 | 7.3 | 7.9 | 8.1 | 10.5 | 19.5 | 18.0 | 20.0 | 28.9 |
|       | (1.3) | (1.4) | (2.3) | (1.8) | (2.4) | (6.6) | (2.8) | (4.2) | (9.0) |

3. Mean (SD)
Figure 1

Experimental design schematic

Participants to perform a task (i.e. quiet sitting on a chair, standing in an upright position, or lifting and lowering a load) for each of the three motion conditions. Each session (NM, LM, HM) began with quiet sitting while resting metabolic rate (RMR) was collected. Exposure to each motion condition lasted ten minutes with a minimum of a five-minute rest period between conditions. The no motion trial was always presented to the participant first.
Figure 2

Motion platform setup depicting standing.

All motion conditions were performed on a Moog 6DOF2000E electric motion platform. The platform consisted of a 2 by 2 m metal platform with 1.02 m high railings along the perimeter. A canopy enclosure eliminated external horizontal and vertical cues from the participant’s field of vision. Motion conditions varied in amplitude and frequency and were derived from captured wave induced ship motions using linear wave theory that allowed for the profile to vary in magnitude (Lloyd, 1993). Photo credit: Carolyn A. Duncan.
Figure 3

Sagittal view of the lifting task that participants performed on the motion platform.

A bimanual sagittal plane lifting/lowering task required participants to lift and lower a 5.0 kg load (length: 0.327 m; width: 0.327 m, height: 0.270 m) directly to and from a table (width: 1.54 m, depth: 0.52 m; height from floor: 0.72 m) securely situated 0.60 m directly in front of the participant facing the bow direction. Photo credit: Carolyn A. Duncan.
Figure 4

Schematic of 5 degree of freedom ship motions.

Linear equations used to develop all motion profiles are detailed (Equations 1-5). The low motion (LM) profile reflected a 10% increases in motion frequency relative to the original vessel from which the motion profiles were recorded and the high motion (HM) profile was characterized by a 15% increase in frequency and a 265% increase in amplitude relative to the seagoing motion profile.
Figure 5

Energy cost of lifting and HR responses during experimental conditions.

Panel A – A comparison of mean energy cost (MET) and corresponding standard deviations between motion conditions for all tasks. Statistical significant difference ($p<0.05$) from No Motion (*) and from other two motion conditions (**). Panel B – A comparison of mean energy cost (MET) and corresponding standard deviations between motion conditions for all tasks. Statistical significant difference ($p<0.05$) from two motion conditions (**).
