Proceedings of the International Conference of Control, Dynamic Systems, and Robotics
Ottawa, Ontario, Canada, May 15-16 2014
Paper No. 110

Mechanical Energy Expenditure While Maintaining Postural Stability In Shipboard Motion Environments Pt II: Results

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Abstract- The aim of this study was to examine the mechanical work performed by different joints in the human body and to correlate it with metabolic energy expenditure. The motivation for this was to better understand human performance at sea. Long-duration ship activities aggravate the chances of various motion disorders including motion-induced fatigue, motion sickness, sopite syndrome, and nausea. These disorders are major biodynamic barriers that reduce the efficiency of crew members and ship operators during operational tasks. The methodology of this research included developing a mathematical model of the human body to calculate the mechanical work expended while maintaining balance. This will aid in understanding the performance of humans during shipboard tasks and also help in formulating strategies to improve the efficiency of human performance. Experimental data from human subjects were collected on a ship motion simulator for twelve different deck motion conditions representing a typical frigate operating in four sea states with three ship headings relative to the principal wave direction. Data were collected using a motion capture system, foot pressure sensors, a load cell, and a metabolic analyzer. The mechanical work performed by the human body and individual body joints was calculated by developing a ninety-six degree of freedom mathematical model. This paper presents the results on variation of metabolic levels with sea severity, variation of metabolism demands with gender, correlation between mechanical work and metabolism, direct comparison of mechanical work with metabolic energy, and distribution of mechanical work among 14 body joints as a function of deck motion. The results of this research provide significant information towards understanding the impact of ship motion on human performance which can contribute to improvements in operational planning and ultimately safety of shipboard personnel.

Keywords: motion-induced fatigue, metabolism, shipboard postural stability

1. Introduction

An experimental laboratory-based study was undertaken to investigate the effect of ship deck motion amplitude and characteristics on human postural stability. Specifically, this was investigated by considering total metabolic energy consumption and the distribution of mechanical work associated with various joints of the human body when subjects were exposed to different deck motions. To realize the experiment, a MOOG 2000E six-degree-of-freedom motion base was fitted with a platform representing a section of ship deck. The motion platform was commanded to reproduce the simulated angular deck motion response of a typical frigate to a long-crested seaway and different ship operating conditions. The four sea states considered were based on a Bretschneider wave spectrum having significant wave heights of 1, 2, 5, and 7 metres and corresponding most-probable modal periods. The ship response was also simulated for ship headings resulting in pure roll motion, pure pitch motion, and combined motion including all of roll, pitch, and yaw motions of the ship. This resulted in 12 deck motion conditions. Ten fit human subjects having minimal previous experience maintaining balance in a shipboard motion environment participated in the experiment. The subjects and motion base were instrumented to record transient motion of 14 primary body segments, time-varying foot pressure distribution, time-varying metabolic energy consumption, and foot reaction forces and moments between one foot and the deck. The latter, combined with a developed 96-degree-of-freedom dynamic model of the human body could be used to solve for all body joint reaction force and moment components and, ultimately, the mechanical work performed by each body joint as a function of time. The details of the experiment are provided in the companion paper "Mechanical Energy Expenditure While Maintaining Postural Stability In Shipboard Motion Environments Pt I: Methodology" (Kaur, 2014). The current paper focuses on the results obtained from the experiment and their interpretation.

2. Metabolic Energy Variation with Ship Motion

2.1. Comparative Analysis of Metabolic Energy for Different Motion Types

Results from this study show that the metabolic energy consumed while maintaining balance for all ship motion types increases as the sea roughness increases. Numerical values are provided in Table 1 and presented graphically in Figure 1(left).

Table 1. Metabolic energy variations with motion (Legend: SM-Ship Motion; E_{S_n}-Rate of energy expenditure for particular sea state)

SM	E_{S_1}, W	E_{S_2}, W	E_{S_3}, W	E_{S_4}, W
PRY	160.9	163.5	171.3	179.6
Roll	199.6	203.9	209.5	210.1
Pitch	246.5	250.4	251.5	259.8

In pitch-roll-yaw (PRY) motion, the least and most severe energy levels can be readily distinguished as metabolic levels are 11% higher in the most severe state when compared to the least severe state. Similarly, for roll motion, metabolic levels for the most severe state (i.e., state 4) are increased by 5% as compared to the least severe state (state 1). Pitch motion follows a similar trend where metabolism demand increases by 5% in the most severe state as compared to the least severe state. Overall, all the motion types show an upward trend of metabolic energy as the wave height increases. These metabolic results closely agree with existing literature (Wertheim, 1998; Marais, 2010).

Figure 1 also clearly emphasizes the extent to which the characteristics of the deck motion, in terms of primarily roll, pitch, or combined motions, affects metabolic energy consumption. This is relevant as these characteristics are dependent on the selected ship heading in a particular sea state. It is observed that in seas characterized by a particular wave height, metabolic energy consumption is lowest for combined motion that includes all of roll, pitch, and yaw; followed by roll motion; and is greatest for pitch motion. Quantitatively, averaged across sea states, roll motion is 22.0% more demanding than combined motion, pitch motion is 22.5% more demanding than roll motion, and pitch motion is 49.5% more demanding than roll. The variation of these values with sea condition varies minimally with wave height in the range considered.

2.2. Metabolic Energy Variation with Gender

Metabolic energy data for 6 males and 4 females were examined to determine the effect of gender on metabolic demands. Figure 1 (right) shows that females experience lower values of maximal O_2 consumption than males. The male energy levels are 30% and 51% greater than females in pitch and combined motions,

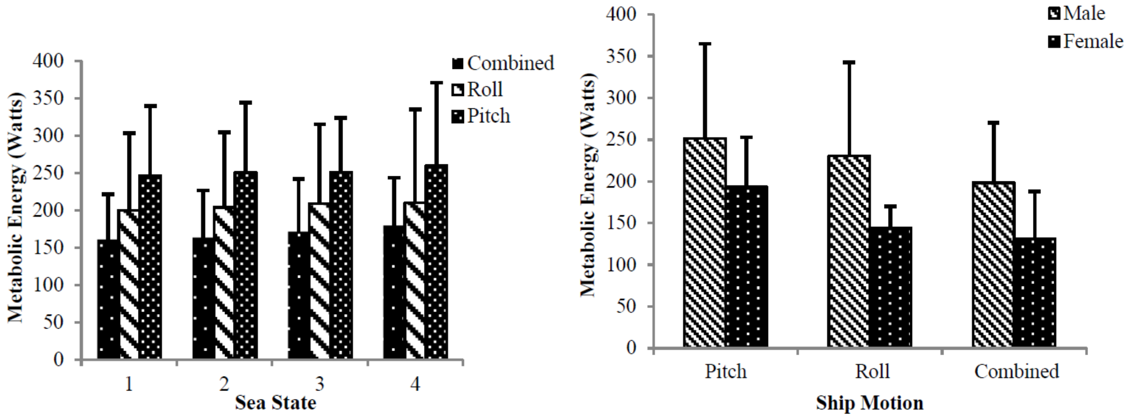

Fig. 1. Metabolic energy with motion severity for combined (PRY), roll, and pitch motions (left); and mean metabolism rate for males and females for pitch, roll, and combined (PRY) motion (right) (lines indicate standard deviations)

respectively. While in the case of roll motion, energy level between sexes differs more, as males used approximately 59% more energy than females.

3. Mechanical Work – Metabolic Energy Relationships

Using Pearson correlation, the calculated total mechanical work of the body was correlated significantly with the corresponding measured expended metabolic energy. An outlier removal treatment was applied to the data prior to correlation testing. Correlation p-values vary from 0.420 to 0.988 for all 120 data sets. However, there exist a few data sets which show little or no correlation at all between the two variables. These were not considered for average and standard deviation calculations. Overall, the average p-values for all data lie in the range 0.6740–0.7835 with standard deviations in the range 0.0809–0.1831 for the 105 work–energy data sets considered. These outcomes are quite significant indicating that both variables are strongly correlated.

3.1. Direct Comparison of Mechanical Work with Metabolic Energy

Figure 3 shows the distribution of the mechanical work to total metabolic energy expenditure, in percent, for the full data set comprising 105 runs (including all ship motion cases and subjects). The figure shows the peak of the hump between 15% and 25% on the horizontal scale reflecting that 19% of the data sets lie in this range. It is apparent from this, that 15%–25% is the most frequent work/energy ratio. The work/energy ratio remains mostly in the 15%–50% range. Also, for 16% of the data sets, mechanical work accounts for 75%-95% of the metabolic energy expended. There are less than 1% of the data sets for which the work/energy ratio is below 5%; in other words, where only 5% of the metabolic energy expended is attributable to mechanical work.

4. Mechanical Work Distribution Among 14 Body Joints

Figure 4 shows the mechanical work distribution among different joints for different motion types for sea state 3 (i.e., 5 metre waves). These data are also representative of other sea states. For roll motion, the ankle, knee, hip, and head-neck joints are major contributors to the mechanical work and perform 39%, 24%, 11%, and 23% of the work, respectively. While the combined lower-extremities, i.e., the ankle, knee,

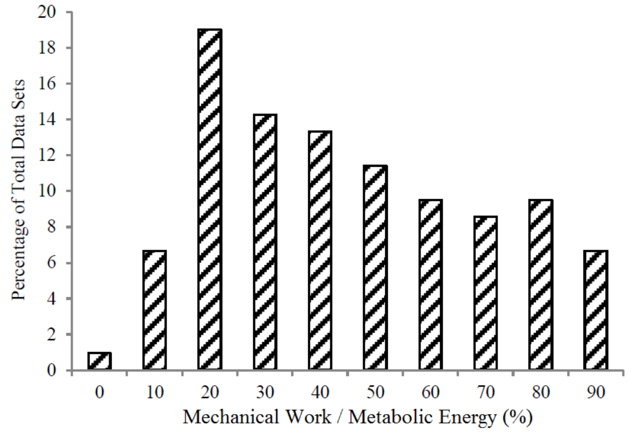

Fig. 2. Distribution of mechanical work/metabolic energy ratio for the full data set

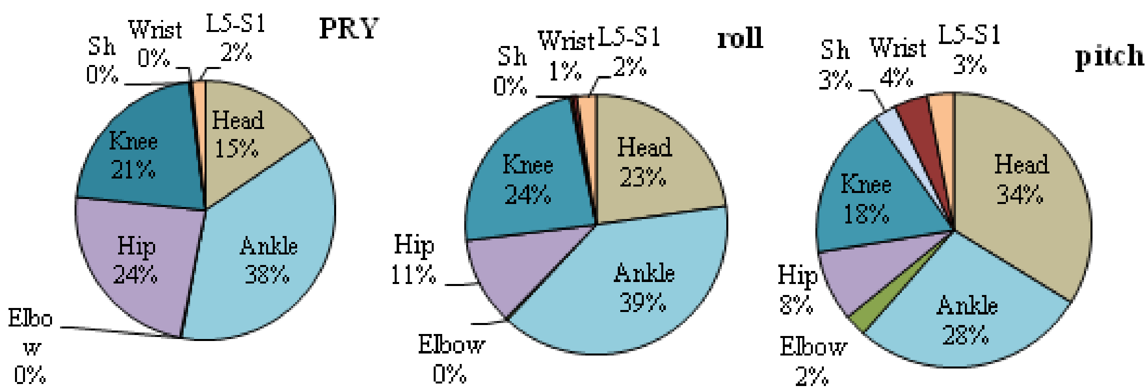

Fig. 3. Mechanical work distribution among 14 joints for 5 metre waves of PRY, roll, and pitch motion.

and hip joints, contribute 74%. The L5-S1 joint is a minor contributor at 2%. Similar results are found for general ship motion, where the ankle, knee, hip, and head-neck joints contribute 38%, 21%, 24%, and 15%, respectively. In the case of pitch motion, mechanical work is more evenly distributed amongst all the body joints including the upper extremity joints, i.e., the shoulder, elbow, and wrist joints, which are insignificant in roll and general motion. The lower extremities, i.e., the ankle, knee, and hip joints, are contributing 54% while the upper extremities, i.e., the shoulder, elbow, and wrist joints, are performing 9% of the mechanical work for stability maintenance in this motion.

5. Discussion

5.1. Metabolism with Sea Roughness

A main objective was evaluation of the effect of ship motion severity on human metabolic demands. Two main findings have been identified from the metabolism analysis: (1) Metabolic energy levels for pitch and roll motion are higher than the general motion case considered; and (2) Pitch motion has a higher metabolic demand than roll motion.

The results conclude that metabolic demands during pitch and roll motions are higher as compared to general/combined ship motion. One important reason behind this observation could be that in pitch and roll, there are greater opportunities for the body vertical axis to drift from the true subjective axis (the vertical axis defined as being perpendicular to the floor, while the true subjective axis of a subject is defined by the direction of gravity). This increases the muscle tone (muscular effort) in order to maintain postural stability (Cheng, 2003). This observation holds true physiologically as well, where utilization of more adenosine tri-phosphate (ATP) for the increasing muscular tension, due to the actin-myosin bond formation, translates into more metabolic energy expenditure. In addition, another important factor is that during roll and pitch motions the visual image of the surroundings perceived by the human visual system does not vary as much as the perturbations to which the human body is exposed. This results in a neural mismatch between perceived visual information by the central nervous system and the applied perturbation effects. This neural mismatch is responsible for higher likelihood of body sway. Moreover, during the data collection sessions, no canopy or visual movie was provided for the subjects in order to make them feel they are actually exposed to sea perturbations. This limited their visual perception and could be responsible for high neural mismatch occurrences.

Another interesting result is that pitch motion energy levels are higher than roll motion. A plausible explanation of this is the fact that during a pure pitch motion, people are most likely to step forward or backward in order to maintain balance. This state requires more metabolic energy compared to roll motion, where the subject is exerting continuous effort during musculoskeletal adjustments, as this resembles walking up and down a hill which requires continuous involvement of muscles for perturbation adjustment (Wertheim, 1998). Also, since the subjects were instructed to keep their right foot fixed on the load cell plate during data collection procedures, this could be responsible for limiting their stance width and hence increasing the musculoskeletal loading to a greater extent due to excursions of the centre of gravity (CoG) during higher pitch motion as compared to roll motion.

Another plausible reason for high pitch motion metabolic energy levels is that in pitch motion, although the amplitude of the simulated ship deck motion is small, the frequency is approximately double that of roll motion. This causes subjects to undergo recurrent musculoskeletal adjustments with high frequency, and therefore more metabolic energy is required as muscles are being continuously involved in generating sufficient joint torque by undergoing translations and rotations.

5.2. Metabolism on Gender Basis

Males tend to expend higher metabolic energy as compared to females. These energy results for the male-female factor are in agreement with the existing literature (Wertheim, 1998; Ferraro 1992). The predominant reason for this could be the difference in body mass index (BMI) between the two genders. The difference in body composition, which represents the amount of muscle, bone, and fat that make up the human body are considered to be an important factor contributing to differences in metabolic energy expenditure between the genders. Males have more muscle and bone mass and less body fat than females. The muscle mass is considered to be a significant factor for higher ATP consumption. Another reason is the fact that the resting metabolic rate (RMR), which is considered as the largest component of metabolic energy expenditure, is 23% greater in males than females (White, 2003). Further, the fact that males tend to have a higher centre of mass relative to females may be contributing factor.

5.3. Mechanical Work – Metabolic Energy Relationships

The third important contribution of this study was to evaluate the relationship between mechanical work and metabolic energy variables with changing ship motion. The relationship between work and energy was studied through two approaches: Pearson correlation and direct comparison.

5.3.1. Mechanical Work – Metabolic Energy Correlation

The significant correlation results showed that metabolic energy demands increase as the mechanical work requirement increases during stability maintenance. These results agree with Hill's results in muscle model studies (Hill, 1938; Woledge, 1991). In these studies, a muscle model was used to show that for isolated muscles, there exists a linear relationship between mechanical work done by muscles and the metabolic energy expended due to utilization of ATP while undergoing contraction due to actin-myosin bonding (Hill, 1938; Woledge, 1991).

However, in the present study, there is the requirement of maintaining postural stability during severe ship motion. Muscle efficiency could no longer be constant/linear in nature. This is because with motion severity there will be greater repetitive postural adjustments made to ensure stability. This results in more frequent musculoskeletal loading and lesser linearity in muscle efficiency (amount of metabolic energy absorbed per unit number of muscle fibres activated) due to haphazard muscle contraction. Therefore, some randomness in the mechanical work–metabolic energy correlation curve is present which is responsible for deviation of p-values from exactly 1.

Another important reason behind this observation could be that mechanical work performed by joints is being calculated through mathematical modelling of the human body (i.e., using an inverse dynamics technique) rather than implementing any invasive technique to detect how many and which particular muscle fibres are contracting by ATP utilization. Besides this, physiologically there are possibilities of utilizing metabolic energy in other physiological processes such as muscle activation, sarcoplasmic reticulum Ca^{2+} pumping (which is a prerequisite for cross bridge formation). Also, it is not necessary that all biochemical energy (i.e., ATP) be used up for mechanical work performed by muscles, as there is energy used up in other activities as well, such as thinking and other mental processes which are not necessarily categorized under mechanical work performed by the muscles. The correlation outcomes are on the basis of these considerations.

5.3.2. Direct Comparison of Mechanical Work and Metabolic Energy

Another significant outcome which was expected from this research was a quantitative estimate of the extent to which mechanical work done by the human body accounts for the metabolism levels of the human. The results show that while the work/energy ratio is quite variable, there is a distinctly noticeable elevation in the rate of instances where the ratio falls in the 15%–25% range. This indicates that for the motion cases considered, the subjects most often expended approximately 20% of their total metabolic energy actuating muscles associated with maintaining postural stability. Further, in 67% of the cases studied, the ratio of mechanical work to total metabolic energy is below 50%. It is recognized that the ratio can never reach 100% due to involvement of other metabolism-utilizing processes within the human body. While evident, consistency between this expected result and the result of the fairly complex sequence of computations involved in this research is considered to be a favourable outcome.

5.4. Mechanical Work Distribution Among 14 Different Body Joints

The last important finding was examination of mechanical work distribution among 14 linking joints while maintaining postural stability with different motion perturbations. Results show that among the various joints, the ankle, knee, hip, and head-neck joints are considered the predominant joints for postural stability for any sea severity level. This could be because calf musculature activation is accompanied by co-activation of the head-neck joint as well as hamstring muscles for keeping the human body movement within limits as soon as the perturbations begin (Horak, 1986). Three sensory mechanisms (i.e., vestibular, visual, and somatosensory systems) are integrated together in order to provide feedback regarding changing position and maintaining it to be stabilized as much as possible. The vestibular system controls the head orientation deviation from the gravitational axis, while the visual system detects head movements due to visual feedback obtained through eye reflex actions. The proprioception system observes leg orientation with respect to the support surface (Cheng, 2003).

A major finding regarding mechanical work distribution is the confirmation that head stabilization during stability maintenance is considered as a significant motor control which provides an orientation-stabilized platform to the human body for smooth progression of body movements. This is done to resist any sway and it is heavily based on the input provided by different sensory systems (i.e., vestibular and visual systems for this task) (Winter, 1995) The existing literature indicates that head-neck muscle fatigue (which limits possibilities for head translation and rotation) results in greater postural sway due to cervical dizziness (Michaelson, 2003).

Another significant outcome of the joint work distribution analysis is that ankle and mixed, i.e., combined ankle and hip, strategies are expected to be activated at less severe and more severe states, respectively. The ankle strategy is characterized by modelling body sway as a single inverted pendulum which allows the body to keep feet attached to the floor of the platform. The hip strategy is characterized by modelling body sway as a double inverted pendulum where the two segments are articulated at the ankles and hip and are most likely active during fast translation on the motion platform (Kuo, 1999).

During less severe perturbations, ankle motion is more likely to limit CoM position within the base of support and it is considered as a dominant factor for balance control by implementing the ankle strategy. As motion disturbance becomes more rapid, the hip joints become mutually involved with the ankles in maintaining stability and this is called the mixed strategy. Flexion at the hip and extension at the ankle joint are activated together for balance maintenance in the mixed strategy. Therefore, this strategy works on the basis of activation of ventral thigh, hip, and knee muscles which are followed by activation of dorsal muscles. Lower extremity joints are more likely to implement the mixed strategy during fast perturbations, although existence of the mixed strategy for less severe ship motion cannot be completely ignored (Kuo, 1999; Horak, 1986).

Another important outcome was that the contribution of knee joint work is significant in all motion types and sea roughness levels. By keeping continuous contact with the ground while keeping the knees straight or flexed, the knee is considered to be performing significant mechanical work by producing muscle tension for this position. This is because keeping the knee in a straight or flexed position requires muscles to be active in order to provide some constraint for any postural strategy and hence mechanical work is observable (Horak, 1986).

From the results, it can be concluded that upper extremity joints contribute insignificantly to the stability maintenance in less severe states and are active only under severe and highly severe sea conditions. While the lumbar-sacral (L5-S1) joint is considered as a minor contributor to the mechanical work for all motion types. The mechanical work for the lumbar-sacral joint falls in the range of 2%–12% for all twelve motion profiles.

Overall, the mechanical work distribution among joints results suggest that some muscle patterns that do not undergo co-contraction in less severe motions, eventually become active as the motion amplitude and frequency increases. This explains the reason for distributing the mechanical work from ankle joints to all other body joints as the motion becomes more severe.

6. Conclusion

The results presented in this paper show that an increase in sea motion severity results in more energy expenditure to maintain stable posture. A high correlation between mechanical work and metabolic energy for all levels of sea state was observed. The multibody dynamic model was used to determine the mechanical work performed by different body joints. The results suggest that the contribution of various joints to the total mechanical work of the body varies for different deck motion conditions. For less severe pitch, roll, and combined motion, the lower body joints are the primary contributors to the work. As the sea state becomes more severe, the upper extremity joints become more involved. The upper body joints are more prominent contributors in severe pitch and combined motions whereas for severe roll motion, the mechanical work continues to occur within the lower extremities.

To summarize, the results suggest that the deck motion conditions have a significant impact on metabolism, mechanical work done, and joint workload of personnel during representative shipboard tasks. It is therefore recommended that human energy expenditure requirements be considered in the planning of shipboard activities, particularly in elevated sea conditions, and that they ultimately also be considered in ship design.

Acknowledgements

Financial support for this research was provided by the Natural Sciences and Engineering Research Council of Canada (NSERC) and Carleton University. Laboratory data collection sessions were conducted with the ethics approval of the Carleton University Research Ethics Board (CUREB). The efforts of all the volunteers and Applied Dynamic Lab members in lab set-up and experimental data collection are gratefully acknowledged.

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