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Mechanical Energy Expenditure While Maintaining Postural Stability In Shipboard Motion Environments Pt I: Methodology

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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 design of the experimental study and the analysis methodology. Detailed results are presented and discussed in an accompanying paper. Ultimately, results of this research project 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

Postural stability is defined as the condition of maintaining the human body's centre of mass (CoM) within its base of support (BoS) limits to avoid stumbling or falling. Postural stability is considered as a prerequisite during various daily life activities such as walking, running, sitting, standing, and performing various physical tasks. It is regarded as a challenging task for crew members and operators during various shipboard activities when ship motion is present. This is because task performance becomes more demanding during offshore operations due to continuous deck perturbations. Physiologically, three neuro-muscular systems, i.e., vision, vestibular, and proprioception are integrated together to maintain postural balance of bipeds by providing feedback to the central processor (i.e., central nervous system) (Winter, 1995). The nonlinearities in neuro-muscular control result from CoM oscillations, described as postural sway. Continuous postural adjustments while in motion-rich environments hinder the routine tasks of crew members and cause added levels of metabolic energy expenditure which manifests itself as motion-induced fatigue (MIF) (Wertheim, 1998; Marais, 2010). In addition, other motion-related disorders occur, i.e., motion sickness, motion-induced interruption (MII), sopite syndrome, etc. All such physiological and biodynamic effects are collectively responsible for reducing the work efficiency, motivation, and morale of ship operators and crew members, which results in increased chances of slips, falls, and injury. So, there is need to understand and minimize, if possible, the obstacles responsible for human performance degradation (Stevens, 2002). This information will be helpful in establishing safe guidelines and procedures regarding effective ship design, better planning and execution of marine operations, ensuring nutrition/health demands, and scheduling proper work-rest ratio, which in turn would decrease the performance degradation of personnel during commercial and warship operations (Stevens 2002; Riola 2006).

To address the issue of energy consumption, an experimental program was designed to measure human energy expenditure required to maintain balance in shipboard motion environments. Interpretation of results relied heavily on a 96 degree-of-freedom multibody dynamic model of a standing human that was also developed and validated as part of this work.

2. Methodology

2.1. Participants

Ethics approval for the experimental trials was provided by the Carleton University Research Ethics Board (REB). Ten participants (6 male, 4 female) ranging between 20 and 27 years old having varying physiological characteristics were used as the experimental subjects. All participants had no or very minimal experience on seagoing vessels. None of them suffered from any musculoskeletal disease, breathing problems, or balance disorders. All subjects were non-smokers.

2.2. Simulated Motion Profiles

Table 1 depicts 12 motion profiles, corresponding to typical frigate motions, generated for use on a MOOG 2000E 6DOF motion simulator that produced representative deck disturbances for the experimental subjects.

Table 1. Motion profiles (legend: MP-Motion Profile; SC-Sea Condition; SWH-Significant Wave Height; SH-Ship Heading; P-Pitch; R-Roll; Y-Yaw)

MP	SC	SWH, m	SH, deg	P	R	Y
1000	1	1	00	yes	no	no
2000	2	2	00	yes	no	no
5000	3	5	00	yes	no	no
7000	4	7	00	yes	no	no
1045	1	1	45	yes	yes	yes
2045	2	2	45	yes	yes	yes
5045	3	5	45	yes	yes	yes
7045	4	7	45	yes	yes	yes
1090	1	1	90	no	yes	no
2090	2	2	90	no	yes	no
5090	3	5	90	no	yes	no
7090	4	7	90	no	yes	no

Using North Atlantic Treaty Organization (NATO) sea state scale standards, motion profiles were generated in increasing sea severity from low wave height (1 metre significant wave height), to medium waves (2 metre significant wave height), to high seas (5 metre significant wave height), and then to severe seas (7 metre significant wave height). Three types of motions, i.e., roll (R), pitch (P), and general/combined ship motion having pitch, roll, and yaw (PRY) were considered. Each of the three motion types had 4 corresponding motion profiles categorized on the basis of wave height, which represented 4 different sea states. It should be noted that in this experiment, sea states 1 through 4 refer merely to four different levels (as shown in Table 1) and must not be confused with the NATO scale of standard sea conditions that uses the term “sea state” to refer to specific ranges of wave elevation and corresponding wave modal period.

2.3. Experimental Set-Up

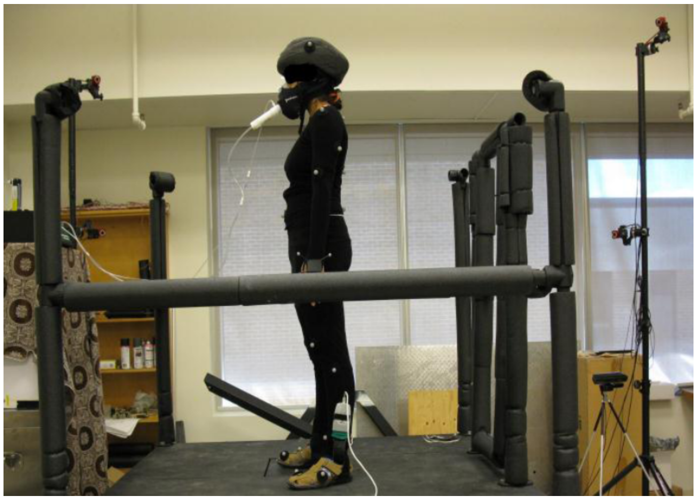

Fig. 1. Instrumentation

The set-up was comprised of 5 major modules as shown in Figure 1. These were:

1. MOOG 6DOF motion simulator;
2. Opti-track motion capture system;
3. Tek-scan insole foot pressure sensor system;
4. Qubit BB1LP respirometry system; and
5. ATI Load cell with force plate ground reaction force system.

The motion platform was fitted with a 2 m by 2 m wooden base to accommodate the force plate. The wooden base of the platform was covered with a high-traction surface in order to minimize slipping possibilities and enhance safety during experimentation. Railings were used to provide safety in the event that a subject lost balance. The Opti-track system was used to collect skeletal motion data with changing ship motion. This set-up comprised of 8 infrared LED cameras arranged to capture the body posture of the subjects as they responded to deck motion. The Velcro motion capture suit with 34 retro-reflective markers attached to it at predefined locations was worn by subjects to identify motion of 15 body segments. Subjects were fitted with pressure-sensing insoles inside their shoes to collect foot pressure data during experimentation. The respirometry system was used for metabolic energy data collection. A mask was placed over the mouth of the test subject and held in place by a head strap for collection of flow rate, O_2 consumption, CO_2 exhalation, and metabolic energy data for different trials. The load cell with the force plate was mounted flush with the surface of the motion platform under one foot to measure the six ground reaction force and moment components. Each piece of equipment was calibrated prior to data collection for every subject.

3. Data Collection

Subjects were asked to stand with their right foot on the load plate at the beginning of data collection. Coordination of kinematic data with load cell data was achieved by setting the origin of the Opti-track global coordinate system (GCS) at the corner of the force plate. Once the subject was ready on the platform, the platform was raised to the neutral position by engaging it and the virtual skeleton of the subject was determined using the ARENA software. The

Tek-scan insoles were connected to the network hub and were calibrated using the Tek-scan step calibration procedure. The BB1LP system settings were verified for respirometry data as well as metabolic energy expenditure data through the Logger Pro meter. To begin the process, subjects were asked to assume a T-pose facing along the positive z-axis of the calibrated Opti-track GCS (where the X, Y, and Z axes represent the medio-lateral, axial, and anterio-posterior directions respectively). The T-pose made actual data collection much easier for ARENA by enabling it to assign a pre-generated skeleton to the subject marker positions. After the T-pose, platform motion was started for actual data collection using the corresponding procedure. While the platform was in motion, participants were instructed to first take three deep breaths while in the T-pose position and tap their right foot on the load plate with exhalation of the third deep breath in order to start synchronized data collection using all equipment (Figure 1). Each motion profile lasted for 360 seconds and there was a rest period of 60 seconds between successive runs while data files were saved and processed. The twelve motion profiles were run in a random order throughout the experimentation. The data collection procedure took 120 to 150 minutes per subject for all 12 motion profiles provided all initial set-up and calibration was performed efficiently.

4. Data Processing

Motion capture data was collected at 100 Hz, so that 36000 frames of data were captured during each 6 minute run. Marker occlusion caused by the padded railings was a prime source of data collection error; though resulting errors in pose determination could be removed using the ARENA software data editing package during the post-processing stage. Another problem occurred from marker swapping and resulted in contortion of the skeletal model during data playback, which was also resolved using the data editing tool. Edited marker data was smoothed using ARENA's "data smoothing" tool by removing high-frequency noise components.

Load cell data was collected at 1000 Hz and down-sampled on a 10 point scale to obtain noise-free data at 100 Hz. The load cell data was also smoothed using a two-pass, fourth-order Butterworth filter to render better quality data for subsequent analysis.

The study focussed on obtaining the following four major outcomes.

1. An inverse multibody dynamic model of the human body.
2. Mechanical work distribution among 14 primary body joints.
3. Metabolic energy variation with deck motion severity and characteristics.
4. Relationships between mechanical work and metabolic energy expenditure.

5. Multibody Dynamic Model Development

Hanavan's 15-segment model was considered for human body modelling, which is based on idealizing the body segments as geometrical solid shapes (Figure 2) (Robertson, 2004). In Hanavan's 15-segment model, the hands and the head are idealized as ellipsoids and all other body segments as circular prisms. Characteristics of various body segments of the human body, i.e., segment mass, segment length, centre of mass (CoM), and principle moment of inertia were approximated using anthropometric data available in the literature (provided by Dempster, 1955; and Drillis and Contini, 1966) (Dempster, 1955; Robertson, 2004). An inverse dynamics approach was applied for inter-segment force and moment calculations based on Newton-Euler equations of motion. All equations of motion were solved using a full-body matrix approach.

In this approach, the human body is modelled as a 15-segment multibody dynamic system with 6 unknown generalized forces (including moments) associated with each segment. Application of the Newton-Euler equations of motion was used to populate a 90×90 coefficient matrix $[A]$ starting with the upper segments and proceeding all the way to the lower foot segments. The three ground reaction force components (F_{grf_x}, F_{grf_y}, and F_{grf_z}) and three ground reaction moment components (M_{grf_x}, M_{grf_y}, and M_{grf_z}) under the right foot (obtained from load cell data) were inserted into the right foot equations; and the left foot ground reaction force and moment components were calculated through the matrix solution. In this way, a total of 90 equations of motion were arranged using the 90×90 coefficient matrix $[A]$ and the associated kinematic data and as-yet-unknown force and moment components.

With the 90×90 full body matrix approach the resulting set of equations is arranged as:

$$[A]_{90\times 90}[X]_{90\times 1} = [B]_{90\times 1} \tag{1}$$

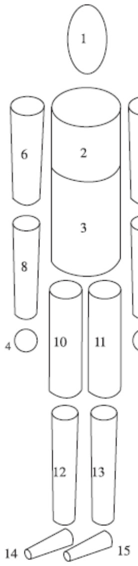

Fig. 2. Hanavan's 15-segment model (Robertson, 2004)

Correspondingly, in principle, it can be solved as:

$$[X]_{90\times 1} = [A]^{-1}_{90\times 90}[B]_{90\times 1} \tag{2}$$

where $[A]_{90\times 90}$ is the 90×90 coefficient matrix, $[X]_{90\times 1}$ is the column vector containing all 90 unknown force and moment components for the 15 segments, and $[B]_{90\times 1}$ is again a column vector representing mass, velocities, and accelerations associated with the unknown forces and moments.

In practice, LU (lower-upper) decomposition was applied for calculation of the 90 force and moment unknowns. This approach was further extended to calculate the mechanical work done by the 14 primary body joints in responding to the ship motion. For instance, the work performed at each joint can be expressed as:

$$W_{\Delta\theta} = W_{\theta_1\to\theta_2} = \int_{\theta_1}^{\theta_2} \vec{M}_{joint} \cdot \mathrm{d}\vec{\theta} \tag{3}$$

where $W_{\theta_1\to\theta_2}$ is the amount of work performed by the joint in changing orientation from θ_1 to θ_2; $\vec{M}_{joint}$ is the moment vector acting at that particular joint; and $d\vec{\theta}$ is the incremental change of joint angle while maintaining stability of the segment. It is recognized that $d\vec{\theta}$ is not strictly a vector quantity. However, over small time increments it is approximated as $\mathrm{d}\vec{\theta} = \vec{\omega}\,\mathrm{d}t$.

6. Discussion

6.1. Full Body Matrix Approach for Human Body Modelling

Three different approaches were considered in a broader project for mathematical modelling of the human body to evaluate the mechanical work performed by different joints. Comparative analysis was applied to select the most accurate and efficient approach for actual data analysis. The first approach was the *Linked Chain Segmental Model* (LSM), which followed two consecutive chains: *top-down* and *bottom-up* for the upper and lower extremities, respectively, to calculate intersegmental forces and moments. The upper chain terminated at the lumbo-sacral (L5-S1) joint, while the lower chain started from the right foot considering the ground reaction force (GRF) components as known forces and moments (from the load plate) and terminated at left foot, where the GRF components of this foot were calculated through the link strategy. The second approach was a combination of the *Linked Chain-Segmental* (LSM) approach and a 42×42 *Half Matrix formulation*, through which all 90 inter-segmental forces and moments were calculated. For this, the upper chain that terminated at the L5-S1 joint, was formulated in the same way as the LSM, while for the lower body, a half-matrix was generated for the lower extremity chain and an inverse matrix solution was applied for force and moment calculation.

The last approach, and the one described in this paper, was called the 90 × 90 *Full Body Matrix* approach. Newtonian full-body matrix mechanics was applied to all 15 rigid bodies and equations of motion were developed using a 90 × 90 coefficient matrix and the inter-segmental joint reaction forces and moments were calculated simultaneously using an inverse matrix solution. A comparative analysis of the three approaches indicated that the *Full Body Matrix* 90 × 90 solution was the most comprehensive approach for dynamic modelling of the human body. It was more accurate and efficient as compared to the other two approaches. This was largely due to the fact that with the *Full Body* 90 × 90 *Matrix* approach, the experimental and numerical errors get more evenly distributed between all rigid body links rather than accumulating at the terminating joint of the chain. In addition, simultaneous calculation of all forces and moments is fast using LU Decomposition in the *Full Body* 90 × 90 *Matrix* approach as compared to the *Linked Chain Segmental* and *Half Linked Segmented-Half Matrix* calculations.

7. Conclusion

Maintenance of postural stability of shipboard personnel while at sea is a major concern in the maritime sector. Comprehensive knowledge of motion-induced fatigue as well as disorders, and work and energy expenditure by humans in different motion environments is required to maximize the crew performance and motivation, and to devise safety standards to provide a better and safer workplace for all shipboard personnel. This was the main motivation behind the current research where mechanical work performed by the body, the work distribution between different joints, and the rate of metabolism required to maintain postural stability for different sea states were investigated. To this end, a three-dimensional multibody dynamic model of the human body was developed and validated in MATLAB. The model is suitable for use in calculating the work performed by different joints in the body to maintain postural stability.

Detailed results of this study are provided in the accompanying paper “Mechanical Energy Expenditure While Maintaining Postural Stability In Shipboard Motion Environments Pt II: Results” (Kaur, 2014).

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