EXAMINING THE RELATIONSHIP BETWEEN PERTURBATION KINEMATICS AND MOTION INDUCED INTERRUPTIONS IN SIMULATED MARINE ENVIRONMENTS

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Examining the Relationship between Perturbation Kinematics and Motion Induced Interruptions in Simulated Marine Environments

by

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ABSTRACT

The purpose of this doctoral dissertation was to attempt to gain a better understanding of when an operator working in a moving environment will experience a motion induced interruption (MII) or execute a motion induced correction (MICs). This was accomplished through a series of experiments and subsequent data analyses which attempted to describe the differences between MIIs and MICs, and define and characterize the postural stability limits of these events when persons are performing standing and manual materials handling tasks. From the results of these experiments it was found that MIIs and MICs are distinctly different phenomena which differ in occurrence, duration and platform kinematics at the time of event initiation. These change-in-support events may also occur well before the theoretical physics-based stability limits have been reached. It was also found that e initiation of these events cannot be predicted solely upon platform perturbation kinematics. Other factors, such as task characteristics and participant experience, may also affect response choice. Therefore, MIIs or MICs cannot be characterized as a last resort event, used only once all other strategies have been exhausted. Since these events may not be a last resource to maintain balance their occurrence may not necessarily suggest greater postural instability than fixed support alternatives and be a good measure of ship operability. Future examination of effects of change-in-support responses such as MIIs or MICs in offshore environments the resultant outcome of the MIC should be examined on a case-by-case basis, and include analysis of ship operability as well as the acute and cumulative injury caused by the performance of the event.

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LIST OF ABBRIEVATIONS AND SYMBOLS

APA: Anticipatory postural adjustment

BoS: Base of support

CoM: Centre of mass

CoP: Centre of pressure

MIC: Motion induced correction

MIF: Motion induced fatigue

MII: Motion induced interruptions

MMH: Manual materials handling

MSI: Motion sickness

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CHAPTER 1: INTRODUCTION AND REVIEW OF LITERATURE

1.1 INTRODUCTION

1.1.1 Current Thinking

Platform motions observed in marine environments pose a significant risk to worker safety. While the strenuous and potentially dangerous nature of the many offshore occupations is obvious even to a layperson, these platform motions are responsible for accidents and injuries related to reduced postural stability and increased work-related energy demands.

Ship motions have adverse effects on the human body that can directly affect performance in many ways including motion induced fatigue (MIF), motion induced interruptions (MIIs) and motion sickness (MSI) *(Figure 1.1)* (Dobbins et al. 2008; Crossland & Lloyd, 1993; Crossland, 1994). Most of the research has focused predominantly on the effects of moving environments on physiological and psychological aspects of human performance (Wertheim, 1998; Schlick et al., 2004). It has been reported that motion primarily reduces motivation due to motion sickness, increases fatigue due to increased energy requirements, and creates balance problems (Wertheim, 1998).

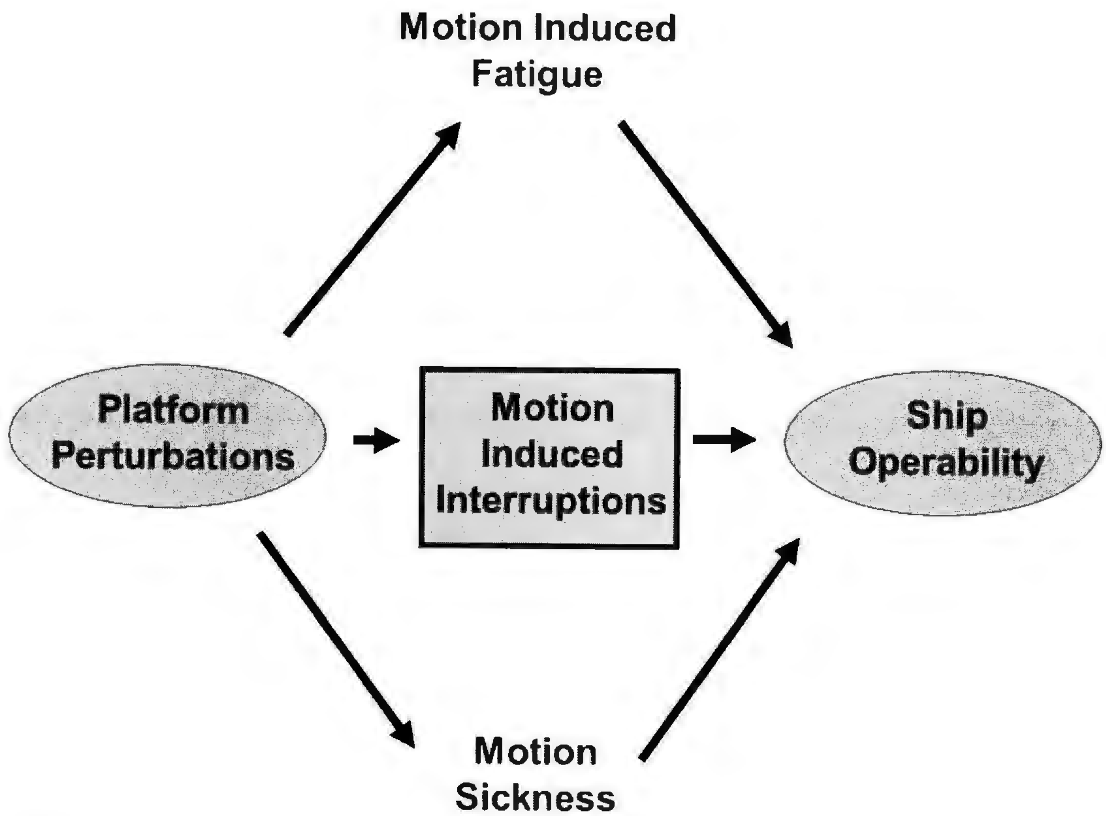

Figure 1.1: ABCD-Working Group Mode of Human Performance at Sea (Adapted from Dobbins et al. 2008)

Previous research undertaken at sea and in simulated environments has found changes in biomechanical variables such as trunk kinetics and kinematics when working in moving environments that may increase risk of musculoskeletal injury (Torner et al., 1994; Kingma et al., 2003; Duncan et al., 2007; Faber et al., 2008; Holmes et al., 2008; Matthew et al., 2007; Duncan et al., 2010; Duncan et al, *2012*). These biomechanical changes are a result of the postural adaptations required to maintain balance in often unpredictable moving environments.

The literature suggests that there are specific events that pose the greatest challenges to postural stability. These events, known as motion induced interruptions (MIIs), are incidents where the displacements and accelerations due to ship motions become sufficiently large to cause a person to slide or lose balance unless they temporarily abandon their allotted task to make a postural adjustment in order to remain upright (Applebee et al. 1980;Baitis et al. 1984; Graham 1989; Crossland & Rich, 1998).

Existing modelling techniques emphasize the use of physics based parameters including platform accelerations and tipping coefficients to predict MIIs (Applebee et al., 1980; Graham 1989; Wedge and Langlois 2003). While these models do demonstrate elements of construct validity, when compared to observed performance data they fail to reliably predict the magnitude and timing of MIIs. This may be due to a lack of understanding by some naval architects and engineers, who develop these MII models of human responses for maintaining or obtaining postural stability in a motion-rich environment. Rather than limiting MII models to basic system dynamics, it has been suggested that including elements of human cognition, learning and abilities to react to perturbations within these models would improve the overall ecological validity of this approach (Langlois et al., 2009).

Reactions that involve the movement of the feet are referred to as change-in-support reactions (Maki & McIlroy, 1997). MIIs assume all corrective foot actions (i.e. moving of the feet) that a person makes are adaptations to maintain postural stability after all efforts to maintain a fixed- foot support have been exhausted. However, more recent research in the fields of clinical biomechanics and motor control suggests that reactions involving movement of the feet, such as those that are defined as MIIs, may be used before the centre of mass (CoM) is translated near the boundary of the base of support. These postural corrections are used instead of other fixed support postural strategies, such as trunk or arm motions well before the stability limits have been reached (Maki & McIlroy, 1997). When examining constrained and unconstrained change-in-support reaction when exposed to unidirectional instantaneous perturbations it was found that participants stepped more frequently than was absolutely necessary to maintain balance when allowed to move their feet as needed (Maki & McIlroy, 1997). These strategies may be preferred over maintaining a fixed support strategy because of the lower physiological requirements and greater biomechanical advantages of the strategy. To the author's knowledge, there is no research that has examined stepping when exposed to wave-induced ship motions in either marine or simulated environments in order to verify these findings.

Physics-based modelling approaches have been used in attempts to predict MII occurrence and frequency by examining the relative instability of the person on a moving environment while performing a particular task (Graham, 1990; Wedge & Langlois, 2003). These models were originally developed as a means of estimating how vessel design and operational demands would affect the stability of a "standard" person and were more focused on vessel performance and design than on human safety and performance. While modelling approaches to MIIs do have their merits, the variability in the manner in which humans maintain or regain postural stability complicates the association between physics-based predictions and human responses. Additionally, current models typically describe stationary standing activities and thus have limited applications in real work environments where workers must perform a large variety of tasks in moving environments.

To improve upon our knowledge of postural stability mechanisms as a response to motion-rich environments an empirical approach may be more appropriate in understanding motion induced perturbations and, thus, preventing acute and cumulative musculoskeletal injuries and improve operator performance. Using an empirical approach MIIs and MICs in motion environments may be observed and the threshold ranges of these events during realistic multidirectional motions can be obtained. These can be used to develop more accurate prediction models and more effective interventions to prevent motion related injuries. From a naval architecture perspective, this approach would also provide better information about ship and workstation design.

1.1.2 Purpose & Hypotheses

The work reported in his doctoral dissertation is an attempt to gain a better understanding of when an operator working in a moving environment will experience a MII or execute a MIC.

The outcomes of this research were to:

1. Describe the differences between MIIs and MICs
2. Define and characterize postural stability limits of persons performing standing and manual materials handling tasks in a moving environment.

The work described in chapters 3 to 7 of this thesis was based on two experiments; *Experiment 1* and *Experiment 2.* Each of these chapters is a separate manuscript prepared for publication with co-authors. *Experiment* 1 is the basis for the writing in *Chapters 3* and *4.* Knowledge gained from *Experiment* 1 was used to develop the experimental design for *Experiment 2. Experiment* 2 is the basis for the writing in *Chapters 5, 6* and *7.*

All this work is an examination of the participants' changes in stance, when standing on a moving platform or, alternatively, performing manual materials handling tasks on a moving platform. In all cases a canopy eliminated the participants' view of the stationary surroundings in the laboratory. The platform was made to move in a manner simulating the motion of the deck of a ship or other structure floating at sea and subject to wave action. The platform could be programmed to move with six degrees of freedom (three translational, three rotational) in patterns simulating vessel responses to wave actions. Several amplitudes were chosen for the selected motion patterns, except for rotation about the vertical axis (yaw), which was not considered a significant variable. In all work, the velocities and accelerations of the platform in each of the other five degrees of freedom at the time of a MII or MIC occurred were key data values of interest.

In *Experiment 1* the participants stood with their feet in prescribed positions under two different conditions (i.e. while constrained as much as possible from stepping away from the prescribed position and, alternatively, while allowed to step away temporarily whenever they felt it was appropriate to maintain stability. Waveform amplitudes in pitch and roll directions were manipulated, and the profiles at the time of each stepping action for each participant were analyzed. Both MIIs and MICs were noted and studied. The purpose, as described in *Chapter 3*, was to determine if there were differences in platform kinematics (i.e. velocities and accelerations in each degree of freedom) during participants' stepping response to the platform motions, between these two standing conditions. In *Chapter 4*, a principal component analysis (PCA) was applied to the same source data used for *Chapter 3*, to discover and examine these potential differences more objectively from a statistical perspective.

In *Experiment 2* the focus was on the MICs of the participants (a different set of participants from those of *Experiment 1*), who performed two stationary standing and two manual materials handling tasks on the same motion platform as used in *Experiment 1*. Waveform amplitudes in pitch and roll directions were manipulated, and the platform motion profiles at the time of MIC for each participant were identified, as described and discussed in *Chapter 5*. In *Chapter 6* the same source data was used to examine the effects of experience and previous exposure by observing differences between initial and subsequent trials. In *Chapter 7* there was further study of the source data from *Experiment 2* for differences due to the type of task, as seen in the velocities and accelerations that produce MICs.

This dissertation tested the following hypotheses:

Hypothesis 1: While being exposed to wave-like platform perturbations the motions that cause MII and MIC are significantly different. This hypothesis was tested in *Experiment 1* and discussed in *Chapter 3* and *Chapter 4*.

Hypothesis 2: MIC occurrence while performing standing and manual materials handling (MMH) can be predicted solely upon platform perturbation characteristics. This hypothesis was tested in *Experiment 2* and reported upon in *Chapter 5*.

Hypothesis 3: The factors of learning and task performance have an influence on MIC initiation. This hypothesis was tested in *Experiment 2* and discussed in *Chapters 6 and 7*.

1.2 OVERVIEW OF LITERATURE

1.2.1 Overview of the Components of Balance

Bipedal stance is naturally unstable since two thirds of the body's mass is positioned above the lower extremities and a relatively small base of suppport (BoS). As a result, even a small deviation from upright stance in the absence of external perturbations can cause postural instability. Balance, also referred to as postural stability, equilibrium and postural control, is a complex motor skill that describes the dynamics of body posture used in preventing falling (Punakallio, 2005). It involves the regulation of static and dynamic relationships between the centre of mass (CoM) of the body and the body's BoS. Balance can be examined and described neurophysiologically, biomechanically, and functionally and is measured by the ability to maintain upright stance while moving (Wade & Jones, 1997; Punakallio, 2005).

Stability is accomplished by maintaining postural orientation and postural equilibrium (Horak, 2006). Postural orientation is the active alignment of the trunk and body with respect to gravity, while postural equilibrium is the coordination of movement strategies to stabilize the CoM during self-initiated and externally triggered disturbances to stability. These processes are accomplished through coordination of ligaments, muscles and neuromuscular controls. Both postural orientation and postural equilibrium are dependent on the support surface, visual surroundings and internal references, task goals and the environmental context (Horak, 2006).

Control of human upright stance involves the input from different orientation senses. The main senses involved are the somatosensory system, vestibular apparatus and vision. Under normal conditions the dependence is primarily on the somatosensory input (70%), with vestibular apparti (20%) and vision (10%) providing complimentary information (Punakallio, 2005; Horak, 2006). The central nervous system relies primarily on somatosensory information to initiate postural responses (Horak, 2006). Reliance on somatosensory information is diminished on unstable contact surfaces. During such occasions the ability to reweight sensory information by placing more dependence on the vision and vestibular mechanisms is critical. The interaction between these systems is not well understood and it is not known whether that maintenance of postural stability is via simple multisensory feedback or a complex optimal model (Maurer, Mergner, & Peterka, 2006).

Knowledge of a body's orientation in space and a context of postural performance are required to maintain postural stability. Orientation in space is primarily vestibular dependent and is based upon the vertical perception of gravity. Typically, the limits of static postural stability are based on the size of the BoS, limited on joint range, muscle strength and the amount of sensory information available to detect its limits (Punakallio, 2005); however, in dynamic situations the context of postural performance is based on a number of factors including: biomechanical task constraints, movement strategies, the sensory environment, postural orientation, dynamics of control, cognitive resources, experience and practice, and perception of the goal and its context (Horak, 2006).

The resultant postural response behavior is non-linear in nature. Increases in external stimuli (e.g. size of the perturbations) do not, necessarily, result in equal increases in the size of response gain. It is hypothesized that stimulus thresholds may be responsible for this stimulus response pattern. However, difficulties with stimulus/response measurement and inherent variation in responses within and between persons limit the current understanding and estimation of threshold values (Maurer et al. 2006). Current knowledge of the area suggests gain and phase of the response varies as a function of stimulus frequency and in relation to the absence and presence of vestibular and proprioceptive cues (Maurer et al. 2006).

1.2.2 Biomechanical Approach to Postural Stability

Biomechanically, postural stability is related to the inertial characteristics of the body segments and inertial forces acting upon the body to maintain upright stance. It can be described in static and dynamic contexts. Static stability is the ability to maintain the CoM within BoS while ignoring minor automatic adjustments. Dynamic stability takes into account the velocity of the CoM as well as the possibility of a changing BoS (Winter, 1995).

The centre of pressure (CoP) helps control the movement of the CoM through the plantar flexor/dorsiflexors to control the net ankle moment and is influenced by the shear forces produced by body segment accelerations (Winter, 1995; Hasan et al., 1996). The range and maximum limits of CoP are greater than that of the CoM and its displacement is a reaction to the body dynamics representing all vertical forces acting on the BoS (Winter, 1995).

1.2.2.1 Biomechanical Modelling and Approaches

Ideally, a good biomechanical model should aim to recreate the structure it is attempting to model by correlating well anatomically and physiologically to the natural system. It should also have tests or experimental procedures for measuring its own parameters and dynamics, and be made up of subsystems of models that can be replaced with more defined and detailed components as they are developed.

Three types of modelling approaches used in postural stability modelling are: dynamical systems, linear systems, and segmented rigid link mechanics. Dynamical systems models are based on the assumption that the current response value depends not only on the current external force/stimuli but also on the preceding time histories. A linear system uses a simple method to explain a complex system. This approach is often too simplistic to describe naturally occurring systems that are often complex and non-linear in their design. Postural stability models that use segmented rigid link mechanics base their models on classic mechanics. While there are advantages to this approach, the active, passive and interactive properties of human tissue makes it difficult to model rigid segment motion of the human body. (Johansson & Magnussson, 1991).

All models use simplifications in attempts to make the problem or research question easier to solve and explain. Some typical modelling simplifications used in postural stability modelling include: 1) grouping all muscles into a single muscle equivalent; ignoring complex joint motion and the effects of ligaments and cartilage; 3) assuming higher level control is a simple position and velocity related feedback; and 4) study only planar motions and simple movement systems. These simplifications make it difficult to accurately model complex naturally occurring systems since they are too large in dimension and structure. Additionally, the dynamics of many of the physiologic components and feedback mechanisms are currently insufficiently understood to accurately model them (Johansson & Magnussson, 1991).

1.2.2.2 Inverted Pendulum Model and Stability Limits

The human postural stability mechanism is modeled frequently using an inverted pendulum model (Winter, 1995). The inverted pendulum model is a segmented rigid link mechanics model comprised of two separate planar inverted pendulums in the medial-lateral and anterior-posterior planes (Winter, 1995). In this model, under static conditions, the vertical projection of the CoM must remain within the range of the CoP to maintain postural equilibrium. This range is referred to as the base of support (BoS) (Hof et al., 2005).

The anterior-posterior inverted pendulum model has pivots at the hip and ankle joints that move synchronously *(Figure 1.2)*. The medial-lateral model has pivots at the hip and ankles. Movement of this model is controlled by four torques moving in the same direction to produce a low maximal moment of the invertors or evertors of the ankle joints and higher maximal movements of the unrestrained hip abductors/adductors. This causes a load/unload mechanism whereby the CoP is in phase with the force of one limb and out of phase with the force of the other limb (Winter, 2001; Winter, 1995).

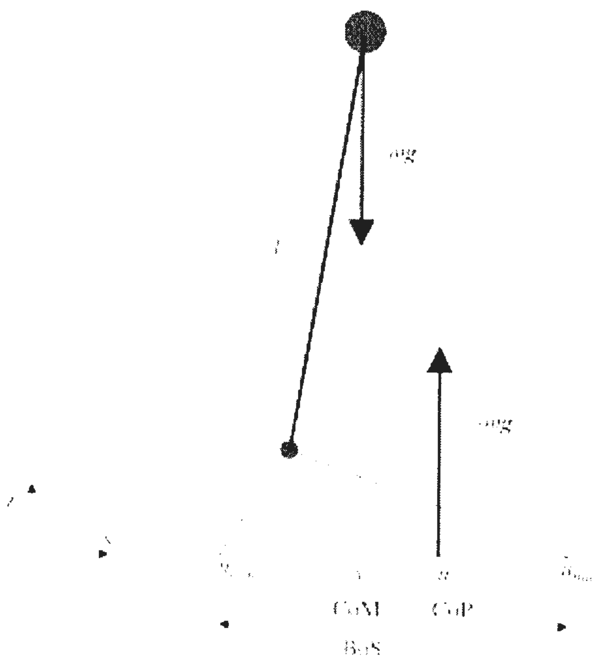

Figure 1.2: Schematic of the anterior-posterior single inverted pendulum model where mg refers to the CoM and "l" refers to the length of moment arm from CoM to the ankle (Hof et al. 2005)

The model suggests that as long as the CoP is kept beyond the CoM with respect to rotation at the ankle, the body will be accelerated back to its upright position. There are four possible outcomes that can occur: 1. the CoM never reaches the CoP and although the pendulum is unstable no immediate reaction is needed; 2. the CoM will pass the CoP and the CoP will accelerate forward to put it in front of the CoM; 3. no movement of the

CoP can prevent that of the CoM from passing outside the BoS as a result of the momentum of the body being greater than the maximal torques produced to keep it within the BoS and a corrective step or move of the trunk or arms with respect to the CoM must be made to maintain balance; and 4. CoM momentum are so great no amount of corrective action maintains upright stance. The margin of stability that the body has is proportional to the impulse needed to unbalance the body (Winter, 1995).

In dynamic conditions velocity, in addition to position of the CoM, must also be taken into account. If the CoM is outside the BoS but has a velocity towards the BoS, stability may be possible. Likewise, if the CoM is inside their BoS, but their velocity outwards, stability may not be possible (Hof, 2005).

1.2.2.3 Functional Stability

It has been suggested that static models such as the inverted pendulum model cannot account for the dynamics of working in realistic work environments and as a result theoretical and functional stability are different (Holbein & Redfern, 1997; Holbein & Chaffin, 1997). Functional stability limits may be as little as 60% of the BoS with accompanying sway angles of 9.2° in the anterior-posteriorly and 15.3° laterally. While ankle muscular strength may not greatly affect functional stability ranges, a variety of factors including differences in internal postural abilities and type of task/activity the person is performing may be responsible for these small stability ranges (Holbein & Redfern, 1997; Holbein & Chaffin, 1997). Further research is needed to determine the nature of the relationship between posture, functional stability range and falling, which specific strategies most effectively increase the functional stability range and their accompanying threshold values (Holbein & Chaffin, 1997).

1.2.3 Postural Stability Strategies

1.2.3.1 Feedforward and Feedback Control

Postural control uses a combination of feedforward and feedback control loops to maintain dynamic equilibrium while performing a task. Predictive (anticipatory) feedforward mechanisms are most predominant when perturbations are predictable and can be prepared for well in advance; while reactive (compensatory) mechanisms are more important in unpredictable environments when there is little or no time to prepare for the oncoming perturbation (Maki & McIlroy, 1997). One type of feedforward control mechanism frequently used is anticipatory postural adjustments (APA). APAs are used to counteract the effects of a perturbation by increasing activation of the postural muscles before the perturbation happens (Aruin, 2003). The major goal of an APA is to counteract reaction forces arising from the primary moment and stabilize the CoM. The type of APA is dependent on the magnitude and direction of an expected perturbation, the properties of the voluntary action associated with the perturbations, and features of the postural task including body configuration (Aruin, 2003). The APA is based on the magnitude of the expected perturbation and does not appear to be affected by the amplitude or size of the task being performed (Aruin & Shiratori, 2004).

Feedback mechanisms can occur *post facto* as a response to the perturbation. They involve successive correction of intended movements and adaptation and learning of motor programs (Johnansson and Magnusson, 1991). The parameters of the feedback loop are based upon those of the APA that occurred before the perturbation (Alexandrov, Frolov, Horak, Carlson-Kuhta, & Park, 2005). Greater reliance is put on feedback mechanisms when prior knowledge of the perturbation is limited (Latash, 1998).

1.2.3.2 Fixed Support and Change in Support Strategies

Many specific strategies are used to maintain postural stability. Strategies are categorized as either "fixed-support" or "change-in-support" strategies. Fixed-support strategies rely solely on lower limb and trunk muscular activations to decelerate the CoM to keep it within the BoS without changing the size or shape of the BoS to maintain postural stability.

There are two types of fixed-support strategies: ankle and hip strategies. The ankle strategy restores postural equilibrium by moving the body around the ankle through production of compensatory ankle torques (Horak & Nashner, 1986). The ankle strategy is somatosensory input dependent and used for small perturbations on firm support surfaces (Winter, 1995; Horak & Nashner, 1986). The hip strategy controls movement of the CoM without any ankle muscle activation through proximal hip and trunk muscles activated in a proximal to distal sequence to produce a compensatory shear force against the support surface. The hip strategy was thought to be only used when ankle strategies cannot produce appropriate torques to maintain postural stability and are often used in combination with ankle strategies (Horak & Nashner, 1986). When alternative strategies exist for a given movement (i.e. multiple combinations of hip and ankle strategies), the system chooses that which best minimizes the potential boundary crossings between different strategies (Johansson and Magnusson, 1991).

Most criticism of fixed-support strategies and the accompanying hypotheses are related to the division of these postural strategies (i.e. when one will be applied instead of the other). Generally, the postulated regions for the ankle and hip strategies are characterized by minimal combinations of muscles which accelerate the body toward the origin of the configuration space; however, the existence of boundaries between the two strategies is difficult to verify experimentally. For example, it has not been possible to use normal and shear ground contact forces to clearly differentiate between strategies. Additionally, differences in the various feedback latencies observed during the strategies could not be identified with necessary changes in acceleration and deceleration characteristic of a particular strategy (Johannson & Magnusson, 1991).

Change-in-support reactions use a sequence of discrete modifiable stages that involve early activation of the hip abductors and ankle co-contraction and a lateral shift in CoM to move the desired limb (Maki, Whitelaw, & McIlroy, 1993; Punakallio, 2005). Through movements of the upper and lower limbs, new contacts with support surfaces are made to increase the size or change shape of the BoS and lengthen the moment arm between the point of action (i.e. the foot or hand) and CoM, so larger stabilizing moments can be used to decelerate the CoM (Horak & Nashner, 1986).

There are fundamental differences between change-in-support reactions and gait (McIlroy & Maki, 1993). Chance-in-support reactions differ from gait by speed of response initiation and the marked absence of functional anticipatory control elements such as muscular activation and large lateral weights shifts (Punakallio, 2005). Small APAs seen in some change-in-support reactions are too small and brief to have major influences on the CoM. Although use of some APAs may be desired, the unpredictable nature of the perturbation may disrupt their formation (McIlroy and Maki, 1999). These factors result in change-in-support reactions having increasingly complex control mechanism that require a heightened dependence on the sensory drive (Punakallio, 2005).

Change-in-support strategies can potentially make larger contributions to stabilization by increasing the range of the CoM displacement that can be accommodated without loss of balance (Maki et al. 2003). Size of the moment arm between the point of action of the contact force and the CoM and resultant stabilizing moments used to decelerate the CoM are also increased during change-in-support reactions (Maki & McIlroy, 1997). Despite their ability to quickly increase stabilization potential change-in-support reactions have possible drawbacks, specifically, relatively small lateral weight shifts during preparation of change-in-support reactions. These weights shifts are dependent on perturbation direction and prior stimulus information and can potentially challenge lateral instability during the reaction (Maki et al., 1993).

Change-in-support reactions occur in both anterior-posterior and medial-lateral directions. Complications in movement due to the anatomical restrictions associated with medial-lateral foot movement and effects of perturbation induced CoM displacement on the unloading of the swing leg cause medial-lateral change-in-support reactions to be more complex than anterior-posterior ones. Anterior-posterior change-in-support reactions simply involve taking a single or multiple steps either forward or backwards, while medial-lateral change-in-support most often involves the crossing over of the unloaded limb. Another less often applied variation of medial-lateral change-in-support reaction involves taking multiple smaller steps. In this variation the perturbation-unloaded limb is moved medially prior to a second laterally directed step with the contralateral foot. A final variation more often utilized during unconstrained standing involves the side stepping of the loaded foot (Maki & McIlroy, 1997).

1.2.3.3 Factors Affecting Postural Response Choice

Research suggests that the choice is much more complex than initially thought. It has been thought that change-in-support reactions were only used after all fixed-support options were exhausted (Horak & Nashner, 1986). However, there are many instances where change-in-support reaction are used well before the CoM is outside the BoS and fixed-support reaction produced torques are insufficient to maintain balance (Maki & McIlroy, 1997; Maki et al., 2003). When considering type of postural response to be used in dynamics situations, the momentum of the of the body, in addition to the static stability margin, must be considered. (Maki et al.,2003). Direction of the perturbation also must be considered. Generally, the increased complexity associated with medial-lateral change-in-support reactions results in anterior-posterior change-in-support reactions being more common than medial-lateral ones. Anterior-posterior change-in-support strategies involving steps backwards are more common as a result of the body's ability to use the toes to maintain balance during forward shifts in CoM instead of having to resort to a change-in-support strategy (Maki & McIlroy, 1997).

Choice of postural stability strategy is also affected by additional factors. Biomechanical factors include: biomechanically related motion constraints (e.g. agonist-antagonist muscle action), the multi-articular nature of some muscle attachments, kinematic constraints as a result of multi-segment body structure, limited variability region joint angular positions and muscle lengths, body state and stance, and external forces resulting from contact with the environment all effect stability limits (Johansson & Magnussson, 1991; Punakallio, 2005; Horak & Nashner, 1986). Environmental constraints (e.g. dynamics of the support surface) specifically affect the length of the change-in-support reaction by increasing the APA and affecting the ability to maintain lateral stability (Maki et al., 2003). Experience and prior knowledge of the perturbation affects type and size of the response choice (Punakallio, 2005; McIlroy & Maki, 1995). Increased exposure and practice reacting to specific perturbations reduces the incidence and size of stepping reactions and increases the APAs used during the stepping reaction (McIlroy & Maki, 1995). Lower leg sensory input limitations affect the amount of information received about the perturbation. Decreased sensory information limits the ability to effectively use APAs during implementation of the reaction (Punakallio, 2005).

All these factors help determine the type, magnitude and variation of the support strategy used (Maki & McIlroy, 1997). Combinations of strategies are also often used (Horak & Nashner, 1986). Generally, there is a tradeoff between speed of compensatory reaction and the stability of the resulting step with the reaction that maximizes dynamic stability for the given situation being chosen (Maki et al., 2003).

1.2.4 Threats to Postural Stability

1.2.4.1 Unstable Surfaces

Until recently unstable surface research has primarily focused on unidirectional motions in the sagittal plane. The responses to sagittal plane instability is to first stabilize the joint closest the perturbation using the gastrocnemius and hamstrings for backwards perturbations and the tibialis anterior and rectus femoris during forward perturbations with some exceptions (Horak & Nashner, 1986).The postural responses are primarily central nervous system driven and occur 100-120ms after the perturbation (Diener, Horak, & Nashner, 1988). They display a marked decrease in APAs that may be a result of the increased possibility of overcompensation to the perturbations causing further instability.

More research related to perturbations in directions other than the sagittal plane has furthered the understanding of perturbation response choice. The amount of attenuation is dependent on the direction of the instability (Aruin, Forrest, & Latash, 1998). Postural responses to unstable surfaces are primarily dependent on original direction and intensity of the perturbation and secondly on flexibility of the trunk in the about the *x* (roll) and *y* (pitch) axes (Carpenter & Allum, 1999). Perturbation frequency and magnitude, prior knowledge of the perturbation, and previous experience of similar perturbations are also influential to response choice (Nawayseh & Griffin, 2006).

Perturbations rarely act in a single plane and most often occur multi-directionally. The asymmetric non-rigid design of the human body causes the contributions from its sensory systems and resultant neuromuscular responses to multidirectional perturbations to differ from planar perturbations (Carpenter & Allum, 1999; Carpenter, Allum, & Honegger, 2001; Preuss & Fung, 2007). Responses to multidirectional perturbation are also distinct between translational and rotational directions (Allum & Honegger, 1993). It has been found that a fixed-support response to multidirectional perturbation occurs in two stages. A leg-based strategy in response to the *y* axis(pitch) component of the motion is followed by a trunk-based strategy in response to the roll component of the motion (Carpenter & Allum, 1999). Multidirectional perturbations also increase the variability of postural synergy groupings during fixed-support reactions (Henry, Fung, & Horak, 1998). Stance width during multidirectional perturbations also affects response characteristics. A narrower stance causes more active horizontal force constraints, larger EMG magnitudes, and larger trunk and CoP excursions during the response (Henry, Fung, & Horak, 2001).

1.2.4.2 Unstable Environments

While much of the work in the fields of clinical biomechanics and motor control have examined the human postural response to unstable surfaces and external perturbations, limited research exists on the effects moving environments (e.g. marine environments) on postural responses. Marine environments pose some unique conditions that can potentially add to the difficulty of maintaining balance. Ship motions produce unpredictable perturbations in six degrees of freedom that affect the body physiologically, psychologically, and biomechanically *(Figure 1.3)*. These motion profiles increase fatigue and adversely affect performance (Wertheim, 1998).

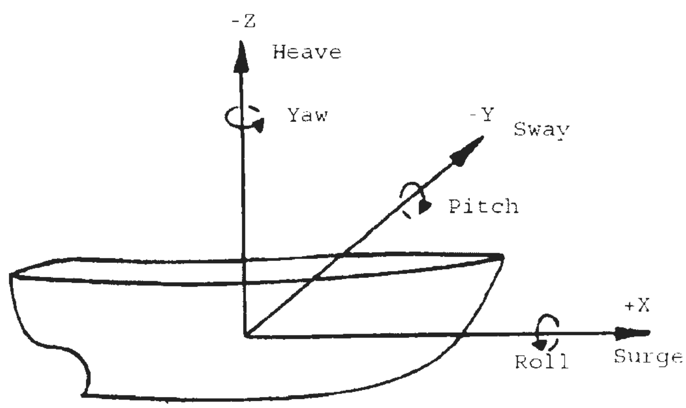

Figure 1.3: A schematic of ship motions about the six degrees of freedom

From a biomechanical perspective, wave-induced ship motions affect both the kinetics and kinematics of the body. Simulated and wave induced platform motions have been found to change whole body kinematics, increase joint loading and increase movement of the CoP during quiet standing and MMH activities such as lifting (Holmes et al., 2008;

Duncan et al., 2007; Faber et al., 2008; Kingma et al., 2003; Matthews et al., 2007; Torner et al., 1994). Joints closest to the perturbation such as the ankles, knees, hips, and low back are most affected (Torner et al., 1994). Trunk kinematic and CoP movement have been shown to increase with increased motion severity and the commencement of change-in-support reactions. This suggests that additional postural adaptations are required to maintain balance in unpredictable moving environments (Duncan et al., 2010; Duncan et al., 2012). Primary direction of the wave motions has also shown to affect postural response choice and resultant kinematics; however, the exact characteristics of these postural responses and how they differ with varying wave conditions is unknown.

1.2.5 MII Modelling

1.2.5.1 Definition

The concept of a motion induced interruption (MII) was first introduced by Applebee and colleagues in 1980 as a method to quantify the ability of humans to function on the ship in the presence of motion (Wedge & Langlois, 2003; Dobie, 2001; Applebee, McNamara, & Baitis, 1980). It was expanded upon by Baitis and colleagues defined a MII as "an occasion when a person would have to stop working at their current ship board task and either change their stance, take a step or hold on to some convenient anchorage to prevent loss of balance" (Baitis, Applebee, & McNamara, 1984). The definition was further expanded upon to incorporate types of motions that would cause an MII, for example an incident where the accelerations due to the ship motions become sufficiently large to cause a person to slip or lose balance unless they temporarily abandon their allotted task to make a postural adjustment in order to remain upright (Crossland & Rich, 1998).

MIIs include three distinct phenomena (Stevens & Parsons, 2002; Baitis et al., 1995; Crossland & Rich, 2000). The most common type of MII is a stumble resulting from a momentary loss of postural stability. This could also be classified as a change-in-support reaction. Other types include sliding caused by the forces induced by overcoming the frictional forces on the deck and very occasionally lift-off as a result of the motion forces exceeding the forces of gravity (Stevens & Parsons, 2002; Baitis et al., 1995; Crossland & Rich, 2000).

1.2.5.2 Current Modelling Approaches

Modelling approaches have attempted to predict the occurrence of MIIs. The first MII model was developed in 1980 by Applebee, McNamara and Baitis. This simplistic model bases the predictions of MII occurrence on only acceleration thresholds and its results in the time domain to estimate occurrence (e.g. five MIIs in five minutes) (Dobie, 2001).

Table 1.1: Summary of MII Modelling Approaches

Model	Type	Inputs	Outputs
Applebee (1980)	Acceleration Threshold	Acceleration Thresholds	# of MIIs in the time domain (e.g. 5 in 5 minutes)
Graham (1989)	Rigid Body	Lateral Force Estimator & Tipping Coefficient	MII rates expressed in the frequency domain (e.g. MII/min)
Wedge and Langlois (2003)	Inverted Pendulum	Composite Index	MII rates expressed in the frequency domain (e.g. MII/min)

The second model developed is Graham's linearized, quasi-static, rigid body model *(Figure 1.4)*. This model represents a significant improvement on Applebee's by predicting that loss of balance during simple gross motor tasks occurs when a person's accelerations exceed a threshold (Crossland et al., 2007). It is based upon the assumptions that lateral and vertical accelerations (as opposed to roll accelerations) are important in predicting when an MII will occur, and that a human standing upright on a deck will react in the same way to accelerations as a passive rigid block with geometrical and inertial properties of a human (Crossland et al., 2007; Wedge & Langlois, 2003).

Graham's model consists of two elements: lateral force estimator (LFE) and tipping coefficient (Graham, 1990). The LFE is an estimate of the amount of lateral force experienced by the rigid body standing aboard using a combination of earth referenced lateral accelerations and ship referenced lateral accelerations caused by the ship. The tipping coefficient (i.e. ratio of lateral to vertical forces) used to determine when MIIs will occur is the ratio of an individual's half stance width to the height of their CoG. Generally, a stance width of 25% of the height is used to predict lateral MIIs and a foot length of 17% of the height to predict anterior-posterior MIIs (Graham, 1990); however, the human ability to move should, theoretically, increase the tipping coefficient (Crossland et al., 2007).

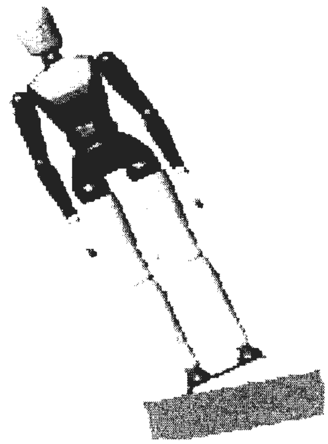

Figure 1.4: Schematic of Graham's Rigid Body Model (Graham, 1990)

Graham's model offers a major improvement over Applebee's model by incorporating frequency of MII occurrence and ship motion into the prediction model. The use of a frequency (i.e. MIIs/min) instead of a time domain approach allows for MII occurrence to be easily expressed and compared. The LFE is only valid when vertical accelerations are near zero because vertical accelerations introduce asymmetry into the situation, therefore, making the model invalid in wave-induced motion situations (Lewis & Griffin, 1997). This limitation was addressed with the generalized LFE (GLFE) that allows for use of non-zero vertical accelerations (Lewis & Griffin, 1997). The model was further improved by factoring in the effects of rotational motion (Graham, Baitis, & Meyers, 1992). Despite these improvements Graham's model still tends to overestimate MII occurrence when compared against real-time data. This may be a result of its lack of consideration of human body's articulated form. Other limitations of the model include: its lack of consideration the effects of accelerations along the plane accelerations, its inability to be used for tasks besides standing, and assumption that the MII reaction is a simple cause-and-effect relationship.

In an attempt to address some of the limitations of Graham's model, Wedge and Langlois (2003) developed a model that takes into account the articulated nature of the human body and based it upon a more realistic human geometry. The model uses the proportions of an average American male, 174cm tall and weighs 78kg, and calculates mass moments of inertia of the segments from regression equations. It assumes that all motions are planar, body segments are rigid and are bilaterally symmetrical, and there are no excessive motions of the upper body (Wedge & Langlois, 2003).The model is broken down into two perpendicular planes (frontal and sagittal). The sagittal plane model consists of an inverted pendulum with a single articulation point at the ankle joint (*Figure 1.5)*, while the frontal plane model represents the human body as a 4 bar linkage with the links representing the ground, left leg and hip, upper body assembly, and right leg/hip (*Figure 1.5*).

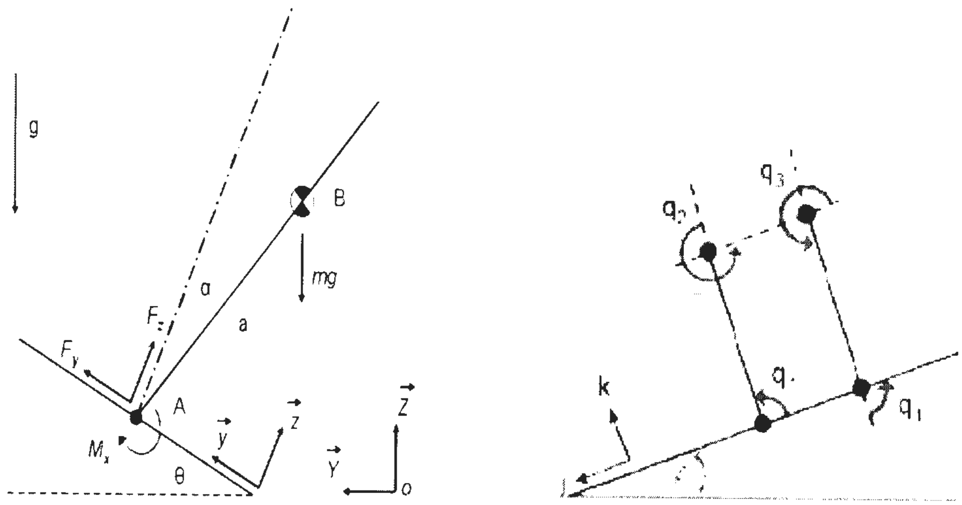

Figure 1.5: Schematics of the Inverted Pendulum (left) and Four-bar Linkage (right) models (Wedge and Langlois, 2003)

The inverted pendulum model is controlled by eight parameters. Three are used to define the subject geometry and inertia (a, m and I_G), three required within MII detection algorithm (the coefficient of friction (μ), the characteristic dimension of the base of support (d) , and combined coefficient threshold ($C_{c\ thresh}$)), and two describing human balance control ($G_1$and G_2) (Langlois et al., 2009). The model's focal point is the outputs of continuous values of the F_y, F_z *and* M_x as a function of time. These variables define incidences when postural stability will be jeopardized (i.e. when tipping or sliding will occur). If the reaction forces required to inhibit sliding (Fy) are greater than the frictional capacity the person will slide. Likewise if the accelerations produce moments that are greater than the forces that the body can produce to counteract them, then tipping will occur (Langlois et al., 2009).Given that the human postural response is not purely physics driven, the MII threshold calculated purely based on rigid body mechanics may not always be an accurate estimation of when an MII will occur. The MII threshold or combined coefficient threshold is based on estimation of the actual human threshold and two gains used to describe human motion (G_1 and G_2). These gains, which are based upon an extensive series of simulation runs, are selected to closely match the model to the overall number of MIIs during the trial and so that a high ratio of the MII occurrences predicted by the model agree with the those observed during the trial (Langlois et al., 2009). If the combined coefficient of the sliding and tipping coefficient is greater than the combined coefficient threshold then an MII will occur.

1.2.5.3 Model Validation Problems with Current MII Definition and Models

Many studies have attempted to validate various MII prediction models (Crossland & Rich, 1998; Crossland et al., 2007; Langlois et al., 2009; Baitis et al., 1995; Crossland & Rich, 2000). These have involved both simulated motion and in situ studies during which standing as well as other manual materials handling tasks were performed.

Validation studies performed on Graham's model found that occurrence of MIIs does not necessarily follow the threshold implied by the rigid body theory used in the model (Baitis et al., 1995). Rigid body theory cannot account for the large amount of variation in tipping coefficients that occur. Tipping coefficients appear to be affected by a number of factors besides purely physics driven rigid body theory. These include type of task, , and s between and within subject differences (Crossland & Rich, 1998; Baitis et al., 1995). In some wave motion scenarios the model predicted the tipping coefficients very accurately while in others the model either over or under-predicted the number of MIIs. MIIs often occurred during small accelerations when the person was well below the tipping threshold, while in some cases MIIs did not occur at points where the threshold had been reached (Baitis et al., 1995). After comparing the model to a number of simulated motion conditions and sea trials involving a variety of tasks in a range of wave conditions, Crossland and colleagues suggested a more practical model that involves the development of tipping coefficients from real time accelerations during actual MIIs in tasks other than standing (Crossland & Rich, 1998; Crossland et al., 2007).

Langlois' articulated model has also been compared to observed MII data in a marine environment (Langlois et al., 2009). Generally, the results were positive with the model closely reproducing the observed MII rate; however, the model only accurately predicted the exact time of occurrence of the MII for 41% of the MII events, with the accuracy of the model improving as deck motions increased. Differences found between the model and observed data may be explained by the large amount of variability between subject MII thresholds. The authors concluded that further validation and testing in simulated six degrees of freedom sea states and marine environments with larger datasets are needed. They also suggest that the MII reaction is not purely kinetics driven and factors that may affect MII thresholds besides those involved with rigid body mechanics such as experience, habituation, and individual physiology must also be considered (Langlois et al., 2009).

Although current MII modelling approaches do have their merits, validation studies suggest that MIIs occur at points before a physics-based model would suggest that stability limits have been reached. These findings support previous work that suggests the change-in-support reactions may occur well before a fixed support strategy is unable to maintain postural stability (Maki & McIlroy, 1997). While this idea has been well supported and accepted in the area of biomechanics it has yet to translate over to the area of ship operability and the current understanding of the human postural reaction to ship motions (i.e. MIIs). Results of experimental trials in both simulated and marine environments suggest that in addition change-in-support reactions occur well before stability limits are reached, that as a result do not fit the current definition of a MII. These events, which can be defined as motion induced corrections (MIC) may be preferable over fixed-support strategies because of their lower physiological requirements and greater biomechanical advantages. They also may be used in anticipation of the oncoming perturbation so that the person's BoS is altered in relation to the direction of the perturbation and the CoM to minimize the effects of the oncoming perturbation.

While the idea of MICs challenges the current definition of a MII, it may help explain much of the variability in MII occurrence seen in experimental trials. Many of the change-in-support reactions that occurred during simulated and sea trials may have been MICs. In order to a gain a better understanding of the human response to wave induced ship motion, specifically MIIs and MICs and their effect on human performance and ship operability, an empirical biomechanics and motor control based approach may be used.

Using this empirical approach, the range of stepping thresholds derived from observing actual MIIs and MICs in moving environments is needed. It has been suggested that the current definitions do not accurately represent responses and therefore a model that more accurately considers human postural dynamics instead of looking just at passive tipping coefficients is needed (Lewis & Griffin, 1997). Research to gain the required knowledge for this model should systematically examine the effects of the amplitude, frequency and predictability of lateral and vertical acceleration on postural stability and performance (Lewis & Griffin, 1997).

Research that incorporates empirical statistical based analyses previously established in other biomechanics applications has potentially beneficial applications in human performance related offshore research. For example, they can help determine the stepping threshold ranges of MIIs and MICs while performing a variety of tasks in realistic multidirectional motions can be obtained. These threshold values have the potential to be used in the development of more accurate prediction models and while also aiding development of effective interventions to prevent motion related offshore injuries.

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CHAPTER 2: CO-AUTHORSHIP STATEMENT

The dissertation author, Carolyn A. Duncan has made the following contributions to this research:

1. *Design and Identification of the Research Proposal*

Ms Duncan played an integral part in the identification of the research questions and subsequent experimental data. With the mentorship of her advisory committee she formulated research hypotheses, formulated experimental protocols to test these hypothesizes, and performed pilot work to test the experimental protocol.

2. *Practical Aspects of the Research*

Ms Duncan performed all participant recruitment for the experiments of this dissertation. She constructed the experimental apparati with the assistance of fellow graduate students and collected all data included in the manuscripts of this dissertation.

3. *Data Analysis*

Ms. Duncan performed the majority of the data reduction, and all the data and statistical analyses for the manuscripts included in this dissertation. She wrote reduction and analysis scripts in Matlab and performing subsequent statistical analyses in SPSS.

4. *Manuscript Preparation*

Ms. Duncan was the primary author of all manuscripts presented in this dissertation. She formulated each manuscript from the results of the research, and made subsequent edits based on the input from the co-authors attached to the manuscript.

CHAPTER 3: STEPPING RESPONSE DURING CONSTRAINED AND UNCONSTRAINED STANDING IN MOVING ENVIRONMENTS

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3.1 ABSTRACT

The purpose of this study was to determine the differences in human stepping response reaction between constrained and unconstrained standing while being exposed to simulated wave-induced platform motions. Twenty subjects (ten male and ten female), with little or no previous experience recreating or working in offshore environments, performed a constrained and an unconstrained standing task on a six degrees of freedom motion bed while being exposed to two different simulated platform motion conditions. Stepping occurrence was greater during unconstrained standing than constrained standing during both motion conditions. However, no significant differences in platform kinematics were found between stepping cases. These results suggest that stepping occurs more frequently than originally hypothesized. Stepping should not be considered as a last resource when all fixed-support options have been exhausted. This should be taken into consideration in order to ensure ecological validity when developing models to predict stepping occurrence.

3.2 INTRODUCTION

Wave- induced platform motions observed in marine environments pose a significant risk to worker safety. 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 demands. Thomas et al.,(1998) reported that worker fatality rates of Alaskan fishermen were 28 times greater than the general average for all workers in the United States with the greatest percentage of these (26%) being related to falls overboard or on deck. This suggests that platform instability may have a significant effect on worker health and safety.

Previous research undertaken at sea and in simulated ocean environments has found changes in trunk kinetics and kinematics when working in moving environments that may increase risk of musculoskeletal injuries (Torner et al., 1994; Kingma et al., 2003; Duncan et al., 2007; Faber et al., 2008; Holmes et al., 2008; Matthews et al., 2007). These biomechanical changes are a result of the postural adaptations required to maintain and retain stability in often unpredictable moving environments. This literature suggests that there are specific events that pose the greatest challenges to postural stability. These events, known as motion induced interruptions (MIIs), are incidents where the kinematics due to ship motions become sufficiently large to cause a person to slide or lose balance unless they temporarily abandon their allotted task to make a postural adjustment in order to remain upright (Crossland & Rich, 1998). The concept of a motion induced interruption (MII) was first introduced by Applebee and colleagues in 1980 as a method to quantify the ability of humans to function on the ship in the presence of motion (Wedge & Langlois, 2003; Dobie, 2001; Applebee et al., 1980). This was later expanded upon by Baitis and colleagues to include three distinct types of events (Stevens & Parsons, 2002; Baitis et al., 1995; Crossland & Rich, 2000). The most common type of MII is a stumble resulting from a momentary loss of postural stability. Other types include sliding caused by required deck reaction forces in the shear plane exceeding available frictional forces and very occasionally lift-off as a result of the motion forces exceeding the forces of gravity (Stevens & Parsons, 2002; Baitis et al., 1995).

Modeling techniques to predict the occurrence of MIIs have been published (Wedge & Langlois, 2003; Graham, 1990). While these models do exhibit elements of construct validity, when compared to observed performance data, they fail to reliably predict the frequency and timing of MIIs. This may be due to an overly narrow focus on the physics of the problem while not adequately considering broader range of factors influencing human responses for maintaining or retaining postural stability in a motion-rich environment. Rather than limiting MII models to basic system dynamics, it has been suggested that including elements of human cognition and physical abilities to react to perturbations within these models would improve overall the ecological validity of this approach (Langlois et al., 2009).

Current thinking regarding MIIs assumes all corrective foot actions (i.e., moving of the feet) that a person makes are adaptations to maintain postural stability after all efforts to maintain a fixed- support have been exhausted. More recent research in the fields of biomechanics and motor control suggests that reactions involving moving of the feet, such as those that comprise MIIs, may be used before the centre of mass (CoM) is translated near the boundary of the base of support and thus near its stability limits, and instead of other postural strategies, such as trunk or arm motions (Maki & McIlroy, 1997; Maki et al., 2003).

While this idea has been well supported and accepted in the areas of biomechanics and motor control it has yet to translate over to the area of ship operability and the current understanding of the human postural reaction to wave induced ship motions (i.e., MIIs). Results of experimental trials in both simulated and *in situ* marine environments suggest that stepping may occur well before stability limits are reached, thus not fitting the current definition of an MII (Duncan et al., 2010; Duncan, 2012; Langlois et al., 2009). Change-in-support reactions which involve the movement of the feet may occur before all other fixed support strategies that do not involve foot movement have been exhausted. These change-in-support strategies of operator foot adjustments have been termed, in this work, motion induced corrections (MIC), may be preferable over fixed-support strategies because of their lower physiological requirements and greater biomechanical advantages. They also may be used in anticipation of the oncoming perturbations so that the person's CoM is better-positioned within the base of support (BoS) to minimize the effects of the oncoming perturbation.

Though the idea of MICs differs from the current definition of an MII it may help explain much of the variability in MII occurrence seen in experimental trials and predictive modelling. Many of the change-in-support reactions that occurred during simulated and sea trials may have been MICs. In order to gain a greater understanding of the human response to wave induced ship motion, specifically MIIs and MICs and their effect on ship operability, an empirical biomechanics and motor control based approach which can determine if there are differences between MIIs and MICs is needed. To the authors' knowledge, there is no research that has examined the differences in the motions which cause MIIs and MICs and the rates at which these events occur when exposed to wave-induced ship motions in either marine or simulated environments. Therefore, the purpose of the study is to assess the occurrences of MICs and MIIs when subjects are exposed to simulated wave-induced ship motions. The research hypothesis for this study was that occurrence of MICs would be significantly greater than the occurrence of MIIs during exposure to the same motion profile.

3.3 METHODS

3.3.1 Participants

Ten males and ten females (age: 25.57 ± 3.64 years; stature: 175.24 ± 8.08 cm; mass 71.19 ± 12.47 kg) were recruited from a university student population. All participants had little or no experience working in moving environments, were not susceptible to motion sickness, and were free of any known musculoskeletal injury. Prior to commencing the study all participants were presented with a document outlining the study and were given the opportunity to ask questions about the research before signing the consent form. This study was approved by the Human Investigations Committee of Memorial University.

3.3.2 Procedures

Participants were exposed to two different motion conditions while performing two stationary standing tasks. A constrained task required the subject to maintain a fixed posture unless stepping was absolutely needed to prevent loss of balance. This outcome motion was considered to be a MII. An unconstrained task allowed the participant to freely move feet whenever it was felt that loss of balance might occur. This outcome response was considered to be an MIC. In both conditions. participants stood with their feet shoulder width apart in a parallel stance. After each foot movement the subject was asked to return to the original standing position.

Constrained and unconstrained standing cases were performed in two motion conditions. During both conditions participants stood facing the "bow direction" of the platform. All motion conditions were performed on a Moog 6DOF2000E electric motion platform *(Appendix A)* Motion conditions varied in amplitude and frequency and were derived from captured wave induced ship motions using linear wave theory (Lloyd, 1993) *(Appendix B)*. Magnitude and frequency of the motion profile was modified to produce motions that were expected to induce MIIs and MICs while still assuring that the motion bed profiles are realistic to those recorded *in situ*. Manipulation of the motion profiles focused on varying the overall frequency and magnitude of all degrees of freedom. This process allows for systematic changes to each degree of freedom of the motion. Due to its limited contribution to wave-like platform perturbations, yaw was not included in the motion profiles. For the increased amplitude condition, the amplitude of the pitch and roll directions was increased by a factor of 2.25 *(Appendix C)*.

Exposure to each motion condition lasted ten minutes with a minimum of a 5 minute rest period between conditions. The standing performances were videotaped and occurrence of stepping reactions was identified from the video records. A canopy placed on the motion platform minimized the effects of visual cues such as an earth-fixed reference. All trials were randomized for each participant to minimize potential learning and fatigue effects.

3.3.3 Data and Statistical Analysis

MIIs and MICs were recorded during each session and later verified from video records. MIIs and MICs were to be considered any instance when the subject stepped from their original position or grabbed the guard rail during the trial. Any stepping performed within one second of another was considered to be part of the previous MII or MIC. MIIs and MICs were grouped based on direction of stepping. Platform velocities and accelerations in each degree of freedom at the time of initiation were algebraically determined from the corresponding motion profile equations. The moment at which the foot of the participant begins to leave the ground to step was considered the point of initiation.

A student t-tests were used to determine if differences between MII and MIC occurrence and mean velocities and accelerations were significant. All statistical analyses were performed using the software package SPSS for Windows (Release 16.0.0, SPSS Inc.).

3.4 RESULTS

Occurrence of stepping differed significantly between unconstrained and constrained standing *($p<0.01$) (Figure 3.1)*. During unconstrained standing subjects stepped more frequently than during constrained standing in both motion conditions. During the baseline condition stepping mean stepping was 13.90 events and 2.05 events for unconstrained and constrained standing respectively. Likewise, during the increased amplitude condition, mean stepping events were 27.40 and 7.00 for constrained and unconstrained standing respectively. Occurrence of both constrained and unconstrained stepping significantly differed between motion conditions *($p<0.01$)*. Increases in both constrained and unconstrained stepping occurred with increasing of the amplitude of the pitch and roll motion waveforms. Large standard deviations identify that during both motion conditions stepping was highly variable between participants.

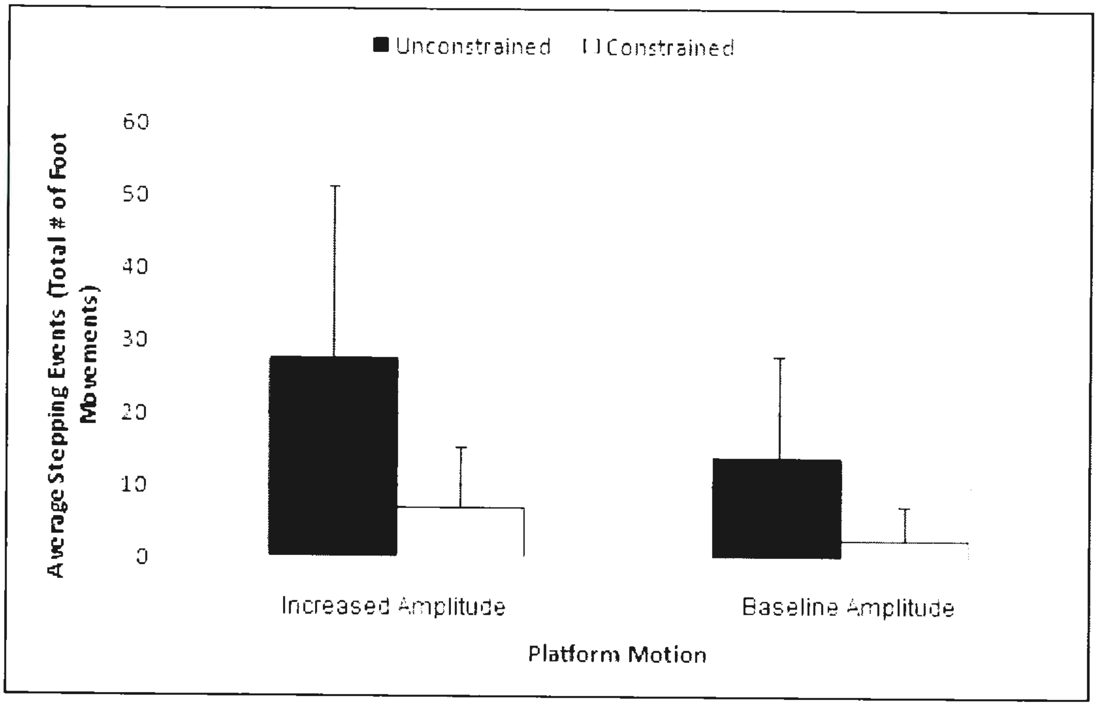

Figure 3.1: Average participant unconstrained and constrained stepping occurrence for each motion condition with standard deviations.

Due to low stepping occurrences during baseline amplitude motion condition statistical analysis was not possible for this condition. Therefore statistical analysis was only performed for the increased amplitude condition. Pre-hoc analyses of the data determined that the data were normally distributed and there was homogeneity of variances. Therefore, students' *t*-tests could be used. No significant differences ($p > 0.05$) in mean velocities or accelerations between MIIs and MICs were found for forwards or backwards stepping events *(Tables 3.1 and 3.2).*

Table 3.1: Mean platform velocities (and standard deviations) during forwards and backwards MII and MIC

	Backwards		**Forwards**	
	MII	**MIC**	**MII**	**MIC**
Sway (m/s)	0.06 *(0.62)*	0.00 *(0.63)*	-0.09 *(0.66)*	0.01 *(0.64)*
Surge (m/s)	0.15 *(0.97)*	0.13 *(1.07)*	-0.19 *(1.18)*	-0.12 *(1.08)*
Heave (m/s)	0.03 *(0.66)*	0.00 *(0.67)*	-0.02 *(0.65)*	-0.02 *(0.67)*
Roll (deg/s)	2.36 *(8.46)*	0.98 *(9.04)*	1.55 *(9.90)*	-0.94 *(9.44)*
Pitch (deg/s)	0.58 *(6.40)*	-0.16 *(6.58)*	-0.59 *(6.48)*	0.32 *(6.55)*

Table 3.2: Mean platform accelerations (and standard deviations) during forwards and backwards MII and MIC

	Backwards		**Forwards**	
	MII	***MIC***	***MII***	***MIC***
Sway (m/s^2)	-0.01 *(0.48)*	-0.02 *(0.48)*	0.04 *(0.37)*	0.02 *(0.47)*
Surge (m/s^2)	0.05 *(1.01)*	0.07 *(0.97)*	0.30 *(0.94)*	-0.11 *(0.92)*
Heave (m/s^2)	0.05 *(1.00)*	-0.05 *(1.02)*	0.02 *(0.98)*	0.09 *(1.05)*
Roll (deg/s^2)	-4.44 *(9.92)*	-3.74 *(9.80)*	4.52 *(8.63)*	3.24 *(9.61)*
Pitch (deg/s^2)	-2.39 *(12.00)*	-0.25 (11.87)	1.52 *(12.31)*	-0.58 *(11.92)*

3.5 DISCUSSION

It has been suggested that wave-induced ship motions have a number of effects on the human body that individually affect human performance, including: motion induced fatigue, motion sickness, and motion induced interruptions (Dobbins et al. 2008).Previous research suggests that the current standards and definitions do not accurately represent the human postural response to wave-induced ship motions Langlois, 2009). Attempts to validate modeling standards used for MII prediction have found that current models do not account for the large amounts of variability and MII initiation appears to be affected by a number of factors besides purely physics based mechanisms (Baitis, 1995; Crossland, 2007; Langlois, 2009). Lewis and Griffin (1997) further suggested that a model that more accurately considers the human postural dynamics instead of looking only at passive tipping coefficients is needed to gain a greater understanding of postural response to wave induced platform motions. The purpose of the current study was to assess the occurrences of MICs and MIIs when participants are exposed to simulated wave-induced ship motions in attempts to determine if constrained or unconstrained foot placement has a significant effect on stepping initiation. Results of this current study found that stepping frequency was significantly greater when subjects were not asked to maintain a constrained foot position, thus confirming the hypothesis that postural response to wave-induced ship motions is not purely a physics-based response and when given the choice, subjects will step more frequently and likely well before stability limits have been reached (Maki and McIlroy, 2003). These results also support the need to consider MICs, where stepping in some instances is preferable to fixed support strategies because of their lower physiological requirements and greater biomechanical advantages.

The current definitions of MIIs and MICs states that MIIs occur only after all other postural control strategies have been exhausted, while MICs occur as an alternative strategy to other fixed support strategies. Based upon these definitions it was hypothesized that MIIs were reactive in nature occurring less frequently than MICs and as a result of greater platform kinematics than MICs, while MICs were anticipatory in nature occurring more frequently, as a result of lower platform kinematics than MIIs. While results of this present study did reveal significant differences in event occurrence, no significant differences in platform kinematics associated with MIIs and kinematics associated with MICs were found. These results may be a result of the between-subject variability attributable to the innate variability between participants as well as other factors which may influence response choice. This resulted in participants stepping during moments of both positive and negative velocities and acceleration and deceleration, in turn, caused mean values at the initiation of MII and MIC events to be very small. Therefore, no significant differences between the groups were found. While using the absolute values of the platform kinematics would eliminate this near-zero central tendency it would also lose critical directional component of the perturbation which has been shown to influence response direction. Therefore, it was not used in this study. These results support the idea that other factors such as, but not limited to, learning, fatigue and external environmental cues may have a significant effect on foot movement necessary to maintain stability. Future studies should attempt to examine the effects of these potential other factors on response choice in order to gain a more complete understanding of the complex mechanism used to maintain balance in moving environments.

Lewis and Griffin (1997) recommended that in order to develop better predictive models research should systematically examine the effects of the amplitude, frequency, and predictability of lateral and vertical acceleration on postural stability and performance. While this current study supports the idea magnitude plays a significant role in postural response choice it also shows that variability of response choice may make it difficult to predict the exact instance that MII or MIC events will take place. These findings suggest that response choice is most likely situation dependent and experience related and thus supports idea that response choice was highly related to human cognition and other influences that are difficult to quantify (Langlois et al., 2009). In order to accurately predict operator responses, these cognitive, situational, and experience related factors and how they influence the effects of amplitude and frequency and predictability of platform accelerations on postural stability must be considered. Instead of attempting to determine exact platform kinematic values at the time of stepping initiation, development of a probability based model that examines the thresholds of stepping occurrence within a particular scenario may be a more effective approach to modelling potential MII and MIC occurrence. This model would incorporate the frequencies at which MIIs and MICs occur across a range of platform kinematic values to evaluate the likelihood of an event occurring as a result of a wave-induced postural disturbance.

3.6 CONCLUSION

The conduction of this study has led to the following conclusions:

1) Frequency differs significantly between MIIs and MICs for a given motion time-history. These events must be considered as two different and distinct phenomena.
2) Variability within the data suggest that postural response choice in ocean like moving environments is a complex mechanism that is not a purely physics based reaction and other situational, experience, and cognitive factors must be considered.
3) When given the opportunity to step as preferred, stepping occurs more frequently. Given the current definitions of MIIs and MICs human postural responses to wave-induced platform accelerations are most likely classified as MICs and therefore stepping must not be considered a last resort after all other mechanisms have been exhausted, but as an alternative response, and potentially more beneficial response, that may be used instead of a fixed support mechanism.

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CHAPTER 4: A COMPARISON OF PLATFORM MOTION WAVEFORMS DURING CONSTRAINED AND UNCONSTRAINED STANDING IN MOVING ENVIRONMENTS

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4.1 ABSTRACT

The purpose of the study was to determine the differences in platform motion waveforms between motion induced corrections (MIC) and motion induced interruptions (MII) occurrences when standing on a six degree of freedom motion platform. Twenty participants (ten male, ten female) with little or no experience working in marine environments performed a constrained and unconstrained stationary standing task while being exposed to three different motion conditions varying in magnitude and frequency. A principal component analysis (PCA) was incorporated permitting the preservation of temporal characteristics unique to each motion curve in the analysis. An analysis of variance was performed on the derived significant principal component scores to determine if these components were significantly different between constrained and unconstrained standing. Preliminary results of the pitch and roll axes suggest that most of the variability of platform motions between MIIs and MICs can be described by two principal components. The first component which accounted for 80-90% of all variability was a magnitude modifier suggests that there are quantifiable differences in the platform motions that cause stepping during constrained and unconstrained standing. Therefore it is likely that these events are distinctly different and should be considered when examining the human response to wave-induced ship motions and ship operability.

4.2 INTRODUCTION

Offshore environments provide unique challenges to human performance and offshore worker safety. Research suggests that wave-induced platform motions have psychological, physiological and biomechanical effects on human performance (Wertheim, 1998). Biomechanically these changes are a result of the postural response required to maintain balance when exposed to these continuous multi-directional platform perturbations. Research suggests that these motions have significant effects on joint kinematics, and foot centre of pressure that may potentially increase the risk of musculoskeletal injury when standing and performing work related manual materials handling tasks (Torner et al., 1994; Faber et al., 2008; Kingma et al., 2003; Holmes et al., 2006; Duncan et al., 2007; Duncan et al., 2010; Matthews et al., 2007).

Threats to postural control and balance can potentially have adverse effects on ship operability. The naval engineering community has suggested that particular motion perturbation events during which the operator must temporarily cease the performance of the activity that they are performing and move their feet to maintain balance are particularly detrimental to ship operator performance. These events known as motion induced interruptions (MII) have been defined as "an incident where the accelerations due to platform motions become sufficiently large to cause a person to slide or lose balance unless they temporarily abandon their allotted task to make a postural adjustment in order to remain upright" (Crossland & Rich, 1998). MIIs include three distinct phenomena: stumbling resulting from a momentary loss of postural stability; sliding as result of forces induced by the perturbation overcoming the frictional forces on the deck; lift-off as a result of the motion forces exceeding the forces of gravity (Stevens & Parsons, 2002; Baitis et al., 1995; Crossland & Rich, 2000). The most common type of MII is a stumble resulting from a momentary loss of postural stability (Stevens & Parsons, 2002; Baitis et al., 1995; Crossland & Rich, 2000).

Attempts by the naval engineering community to model and predict the occurrence of these events have been made (Graham et al., 1992; Wedge & Langlois, 2003). While these models do have their merits they lack ecological validity and assume that MIIs are purely physics-driven reactions that occur only once all other strategies of postural control that do not involve altering the shape of the base-of-support have been exhausted (Langlois et al., 2009). Validation of these models suggest that that MIIs occur at points before a theoretical physics-based stability limits have been reached and, thus, are not purely kinetics driven (Langlois et al., 2009). Therefore, factors that may affect MII thresholds besides those involved with rigid body mechanics such as experience, habituation, and individual physiology must also be considered (Langlois et al., 2009). These findings support previous work that suggests the MIIs may occur well before a fixed support strategy is unable to maintain postural stability (Maki & McIlroy, 1997).

While this idea has been well supported in the biomechanics community it has yet to translate over to the naval engineering community and the current understanding of the human postural reaction to wave induced ship motions (i.e. MIIs) (Maki & McIlroy, 1997). Research suggests that stepping occurs well before stability limits are reached (Duncan et al., 2010). These stepping events are not consistent with the classical definition of a MII and therefore instead may be defined as motion induced corrections (MIC). These MICs may be preferable over fixed-support strategies because of their lower physiological requirements, greater biomechanical advantages. In order to gain a greater understanding of the human response to wave induced ship motion effect on ship operability an empirical biomechanics and motor control in moving environments is needed. Research that incorporates empirical biomechanical -based analyses previously established in other biomechanics applications has potentially beneficial applications in human performance related offshore research.

One of the major limitations of parametric analysis techniques, that are typically used to examine biomechanical data, is that it loses the temporal characteristics of the variables and thus only is representative of discrete events with a waveform (Wrigley et al., 2005; Deluzio et al., 1997). As a result of this, parametric analysis cannot analyze time dependent variables in a relevant way. Principle component analysis (PCA) is a non-parametric multivariate statistical analysis technique multivariate that allows for the preservation of the unique shape and motion of curves (Wrigley et al., 2006). By discriminating and classifying groups based on an entire waveform (instead of just discrete points) PCA can often identify differences within a dataset that due to the preservation of the shape of motion cannot always be identified using parameter based analysis. This allows for the analysis of the modes of variation by exploring and explaining specific patterns within a group of variables. The patterns of variability can be transformed into uncorrelated components thereby identifying the parameters responsible for the greatest amounts of variability, with most relationships being able to be described by only a few of modes of variation (Wrigley et al., 2006). Within the biomechanics community PCA has been used successfully for a number of applications including examining differences between normal and abnormal gait patterns, variability in lifting characteristics, and principal patterns of variation in electromyography waveforms from specific muscles (Deluzio et al., 1997; Hubley-Kozey &Vezina, 2002; Wrigley et al., 2005; Wrigley et al., 2006).

While previous studies have examined differences between MIIs and MICs using a parameter-based analysis, the time-dependent nature of wave-induced platform motion suggests that key features of motions that are related to the temporal characteristics of the MIIs may be insufficiently described using parametric analysis (Duncan et al., 2010; Duncan et al., 2012). Using a PCA, the temporal characteristics unique to each platform motion waveform can be preserved allowing for the examination of differences in these motions within the time domain. This can help determine if timing of a perturbation in addition to its magnitude plays a significant role in MII and MIC initiation. Therefore, the purpose of the study was to determine the differences in platform motion waveforms between MICs and MIIs occurrences when standing on a 6 degree of freedom motion platform. The hypothesis for this study was:

Significant differences in the platform motions at MII and MIC initiation exist.

4.3 METHODOLOGY

4.3.1 Participants

Ten males and ten females (age: 25.57 ± 3.64; stature: 175.24kg ± 8.08kg; mass 71.19kg ± 12.47kg) participants were exposed to two different multidirectional motion conditions while performing two stationary standing tasks on a six degrees of freedom motion platform. Participants were recruited from a university student population. All participants had little or no experience working in moving environments (i.e. had worked in the offshore industry or heavily involved in recreational boating), were not susceptible to motion sickness and were free any known musculoskeletal injury. Prior to commencing the study all participants were presented with documentation outlining the study and were given the opportunity to ask question about the research before signing the consent form. This study was approved by the Human Investigations Committee of Memorial University.

4.3.2 Procedures

Participants were given instructions designed to induce either MII, or MCI, types of movements. Our goal was to understand if the motions that resulted in a movement event (in either instruction condition) differed systematically. Standing tasks representative of constrained and unconstrained standing tasks were performed in the two motion conditions. During the constrained standing task the participants were instructed to move their feet only when absolutely needed to prevent loss of balance. During the unconstrained standing task participants were instructed to move their feet when they felt it is best to maintain postural stability. After each foot movement participants were asked to return to their original standing position. The constrained task was representative of the demands upon the participant consistent with evoking MIIs while the unconstrained task was representative of demands upon the participant required to evoke MICs. The constrained standing task was representative of MIIs while the unconstrained standing task was representative of MICs. Each motion exposure was performed for both constrained and unconstrained standing. Exposures were ten minutes in length with a minimum of 5-10 minute rest period between conditions. During all the participants faced the bow of the motion platform. During all trials wave perturbations were simulated as if the participants were facing the bow direction on a boat. All exposures were videotaped and occurrence of stepping reactions was recorded. Platform motions and video were sampled at a rate of 60Hz, and were synced using auditory cues.

The data collection was performed on a Moog 6DOF2000E (Moog Inc.) electric motion platform. Motion profiles for the motion conditions were composed of motions about five degrees of freedom (pitch, roll, surge, sway, heave) and were derived from captured wave induced ship motions using a complex linear equation method that allowed for the profile to vary in magnitude (Lloyd, 1993). Due its small contribution to platform perturbations in offshore vessel moving environments, rotation about the vertical axis (yaw) was not included in the motion profile. Severity of the motion profile was modified to produce motions that will likely induce MIIs and MICs while still assuring that the motion bed profiles are realistic to those recorded in situ. Manipulation of the motion profiles focused on varying the overall magnitude and frequency of five degrees of freedom to manipulate the severity of the perturbations. Linear equations from which all motion profiles are detailed *(Appendix B)*. For the low amplitude condition the frequency of all degrees of freedom was increased by 10%. For the increased amplitude condition the amplitude of the pitch and roll directions was increased by a factor of 2.25 *(Appendix C)*. A canopy placed on the motion platform minimized the effects of visual cues (i.e. earth-fixed reference) from surrounding stationary environment from effecting participant's response choice *(Appendix A)*.

4.3.3 Data Analysis

Stepping events for each condition were identified from video records by the principal investigator. Initiation of an event was considered to be the moment at which one foot moved from the standardized position. Other members of the investigative team randomly selected and checked timing of events to insure validity of the initiation times. PCA was performed on wave-induced platform motion velocity waveforms about each degree of freedom using the method described by (Wrigley et al., 2006). For the purpose of this study surge, sway and heave were not examined due to their limited influence on the differences between MIIs and MICs as determined during pilot work. Individual matrices of the motion waveforms about each degree of freedom during the MII and MICs were created. Each individual MII and MIC event was entered as a row vector *(nxp)* normalized to a set number of time points. MII and MIC were defined as point at which participants took a step. Stepping which occurred one second after a previous step was considered to be part of the previous MII or MIC. For the purpose of this analysis each MII or MIC event was cut in a normalized length of 0.5 seconds before and 0.5 seconds after the event occurrence and normalized to 100 points. This time envelope was used so that the platform motions preceding and following the event could be examined to determine if some events may be initiated in advance of an upcoming perturbation. The necessary size of this time envelope to capture this information was determined during prior to commencing data collection. Thus each normalized motion waveform was defined by a 100 point coordinate position vector within coordinate space of normalized points. MIIs and MICs were separated by direction of stepping (forwards and backwards). For the present study MII and MIC initiations during the base amplitude condition were limited and therefore the sample size was not sufficient enough to perform the analysis. The increased amplitude condition yielded 172 backwards stepping and 53 forwards MIIs and 763 backwards stepping and 329 forwards MICs were observed, yielding a 329 x 100 matrix for each degree of freedom for forwards stepping events and a 763 x 100 matrix for each degree of freedom for backwards stepping events. Due to low occurrence, lateral stepping events were not included in this analysis.

Matrices were transformed into principal components using eigenvector analysis of the correlation matrix *(Equation 4.6))*. where "n" *is* observations (i.e. MII or MIC events), " "p is the dimensions, $\underset{p\times p}{S}$ is the correlation matrix, $\underset{n\times p}{X}$ is the data matrix, and $\underset{1\times p}{\bar{x}}$ is the mean of the row vectors (Jackson, 1991).

$$\underset{p\times p}{S} = \frac{\left(\underset{n\times p}{X} - \left(\underset{n\times 1}{1} \times \underset{1\times p}{\bar{x}}\right)\right)' \times \left(\underset{n\times p}{X} - \left(\underset{n\times 1}{1} \times \underset{1\times p}{\bar{x}}\right)\right)}{n-1} \tag{4.6}$$

Each principal component coefficient was interpreted as a single mode of variation describing variability within the entire dataset (Wrigley et al., 2006). Principal component scores for each waveform with respect to each principal component were derived *(Equation 4.7)*, where $\underset{n\times p}{Z}$ is the principal component score for each waveform and $\underset{n\times p}{U}$ is the eigenvector matrix.

$$\underset{n\times p}{Z} = \left(\underset{n\times p}{X} - \left(\underset{n\times 1}{1} \times \underset{1\times p}{\bar{x}}\right)\right) \times \underset{p\times p}{U}' \tag{4.7}$$

These principal component scores are the transformation of the original motion observations into the new coordinate space defined by the principal components. They describe how closely each waveform conforms to the mode of variability represented by each principal component and can be used as a dependent measure in inferential based statistics to determine if any significant differences exist between groups (Hubley-Kozey & Vezina, 2002;Wrigley et al., 2005; Wrigley et al., 2006). Parallel analysis was performed to determine the number of principal components that must be retained to reflect the primary modes of variation within the data set (Jackson, 1991; Wrigley et al., 2005; Wrigley et al., 2006). All scaled eigenvalues and their associated principal components and principal component scores that fell above this line of eigenvalues from the randomly generated data set were retained for analysis.

The relationship between the principal component scores and coefficients was examined by scaling the components to represent the correlation between the principal component and the *j*th time sample using the associated standard deviations (Jackson, 1991). The scaled components were then squared to represent the proportion of variability accounted for by the principal component at each portion of the MII or MIC event time (Wrigley et al., 2006).

Representative graphs displaying the mode of variation captured with the original waveform trajectories were created by adjusting the principal component scores for the amount of variability captured by the multiplying each principal component score by the ratio of the associated eigenvalues and the sum of all 100 eigenvalues expressed as a percentage. Wrigley et al. 2005 suggested that principal components can be described by one of three operators (magnitude, difference and phase shift). Magnitude operators describe a variation in the waveform amplitudes; differences operators describe a change from either having a relatively low to high waveform amplitude or vice versa; phase shift operators describe a change in the relative timing of waveform events. All matrix calculations and graph developments were performed using Matlab (Release R2009a Student, MathWorks Inc.).

Students t-tests were performed on the derived significant principal component scores of each principle component for each degree of freedom to determine if significant differences in motion profiles exist between MII and MIC events of the same type. No comparisons between MICs and MIIs that resulted stepping in opposite directions were made (i.e. forwards stepping MICs were only compared to forwards stepping MIIs). Significance level of $P < 0.05$ was used for all statistical tests. All statistical tests were performed in SPSS for Windows (Release 16.0.0, SPSS Inc.).

4.4 RESULTS

Eigenvector analyses of forwards and backwards stepping events were performed separately. Parallel analysis of the platform motion waveforms indicate that greater than 95% of differences in platform motion variability between MIIs and MICs can be described by two principal components for both pitch and roll.

The first component accounted for 80% and 90% of the variability, respectively for the roll and pitch axis. Qualitative examination of loading curves *(Figures 4.1a,4.3a,4. 5a and4.7a)* and the corresponding reconstructed curves *(Figures 4.1b,4.3b,4. 5b, and 4.7b)* suggest that in all cases this component appears to be a magnitude operator that is evident throughout the waveform with greatest effect at the MII/MIC initiation. Similar analyses of the second component which represents less than 20% of the variability between waveforms suggesting that this component is a difference operator (*Figures 4.2b, 4.4b, 4.6b, and 4.8b)*.Examination of the corresponding loading curves shows that the greatest amount of variability between MIIs and MICs explained by this component occurs before and after event initiation.

While there are visible differences between MIIs and MICs for all components,, statistical analyses of the principal component scores reveal that only the primary component in pitch direction for both forwards and backwards stepping was significantly different between MIIs and MICS *($p<0.05$).*

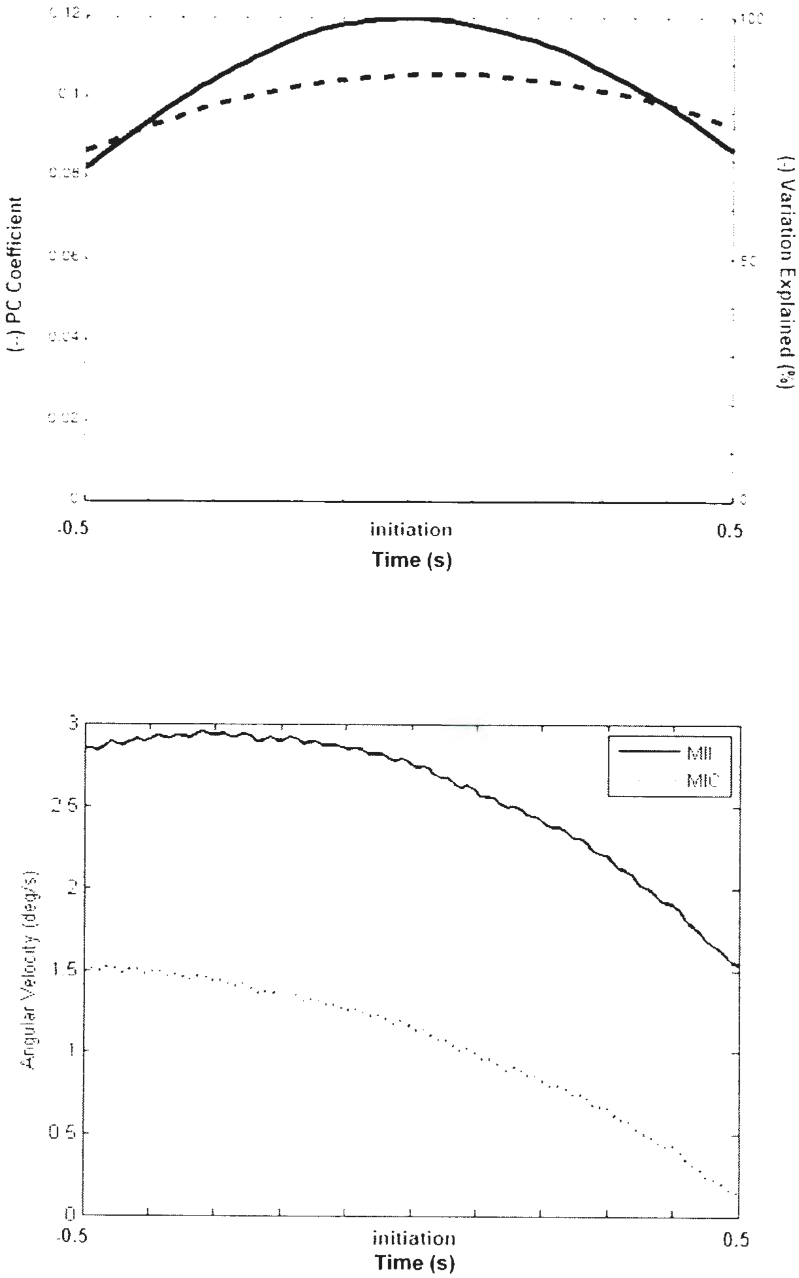
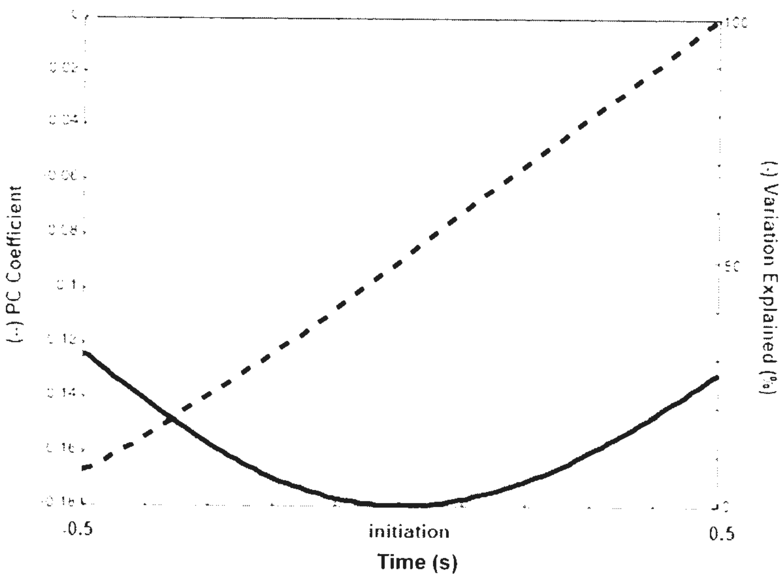


Figure 4.1: (a) The original coefficient of the 1st component of pitch during backwards stepping (- - -) and the coefficients scaled to the percentage of the variation explained (-). (b) Reconstructed waveforms during MIIs and MICs indicated from the 1st principal component score to be a distinct magnitude operator.



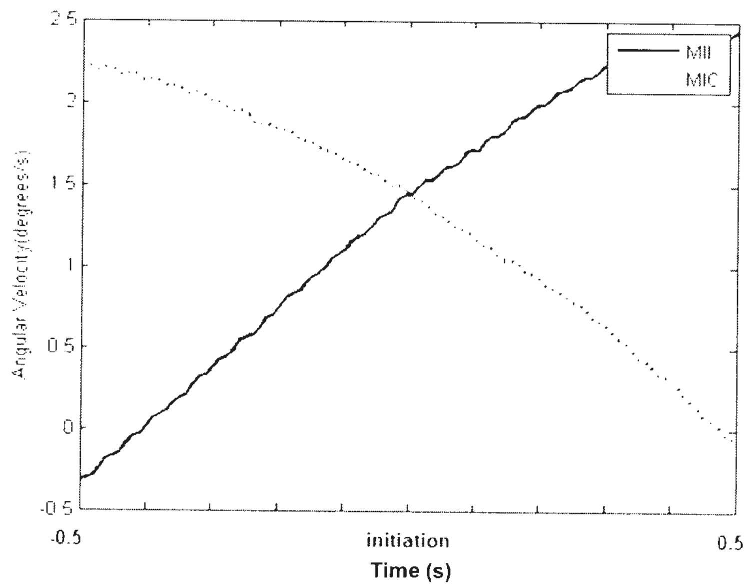


Figure 4.2: (a) The original coefficient of the 2nd component of pitch during backwards stepping (- - -) and the coefficients scaled to the percentage of the variation explained (-). (b) Reconstructed waveforms during MIIs and MICs indicated from 2nd principal component score to be a difference operator

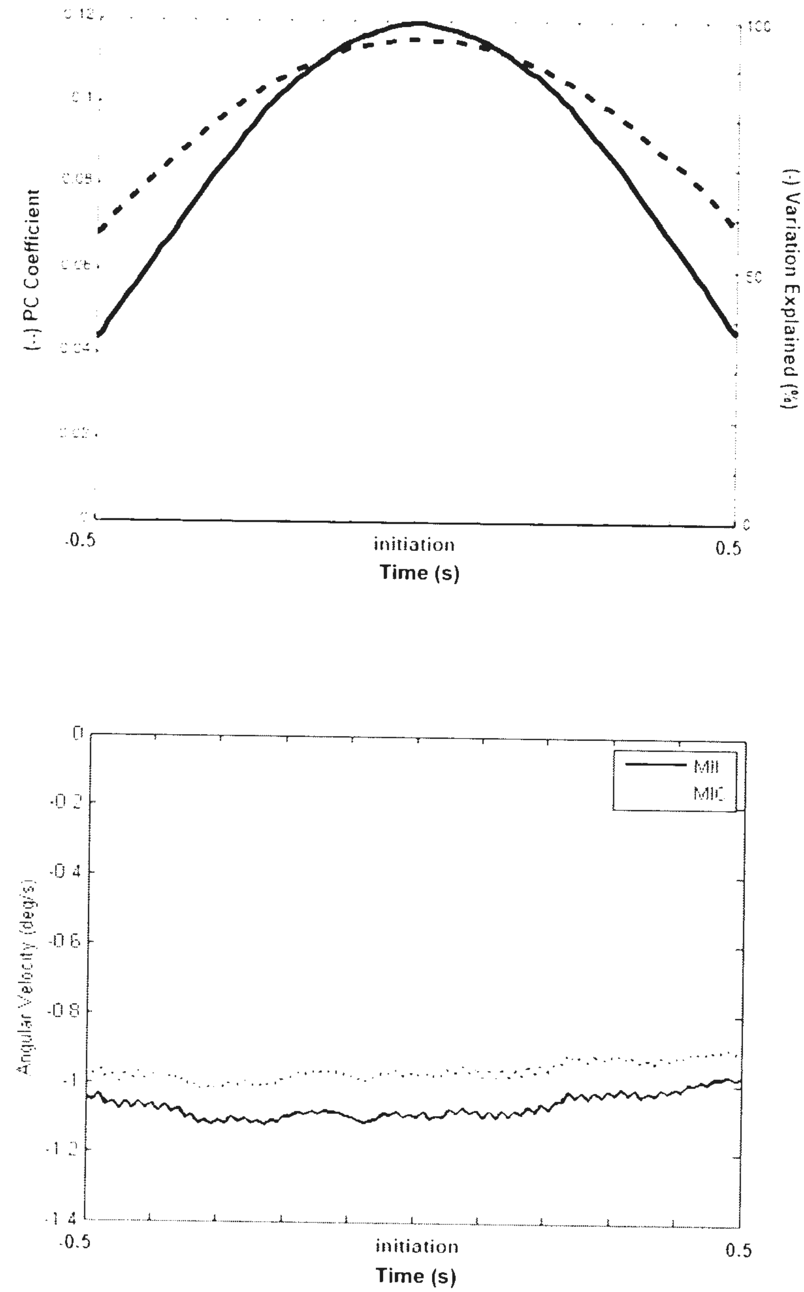
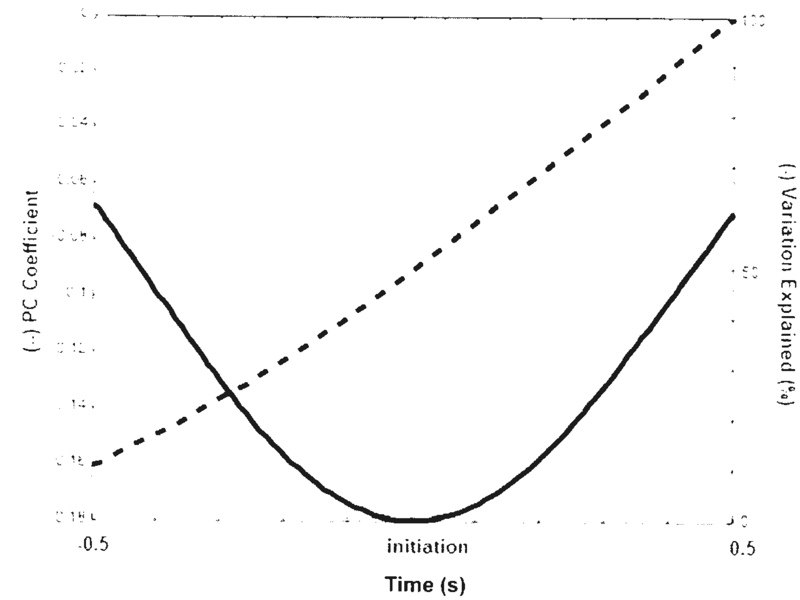


Figure 4.3: (a) The original coefficient of the 1st component of roll during backwards stepping (- - -) and the coefficients scaled to the percentage of the variation explained (-). (b) Reconstructed waveforms during MIIs and MICs indicated from the 1st principal component scores to be a magnitude operator.



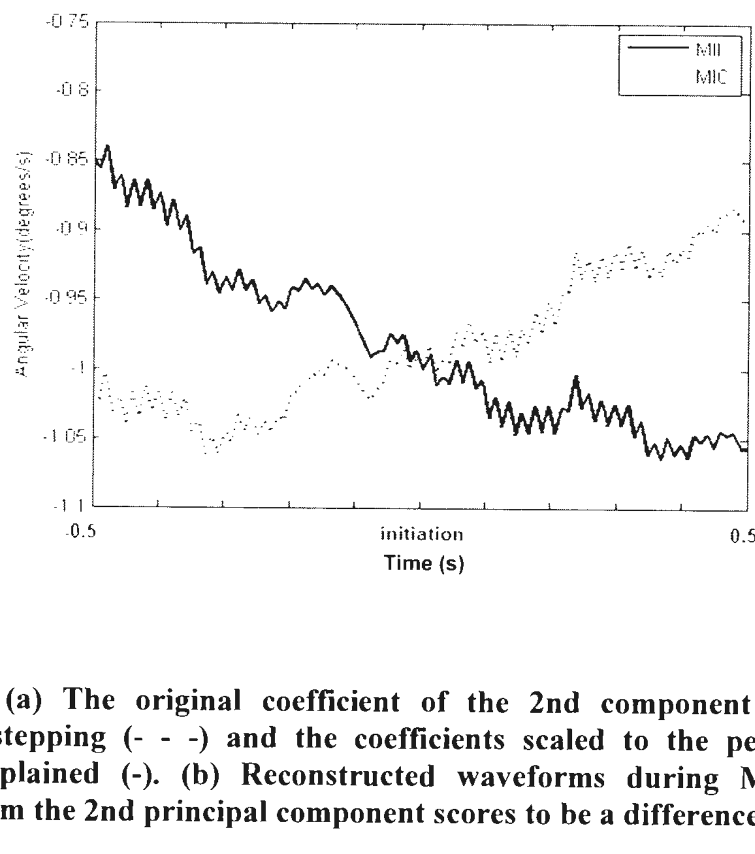
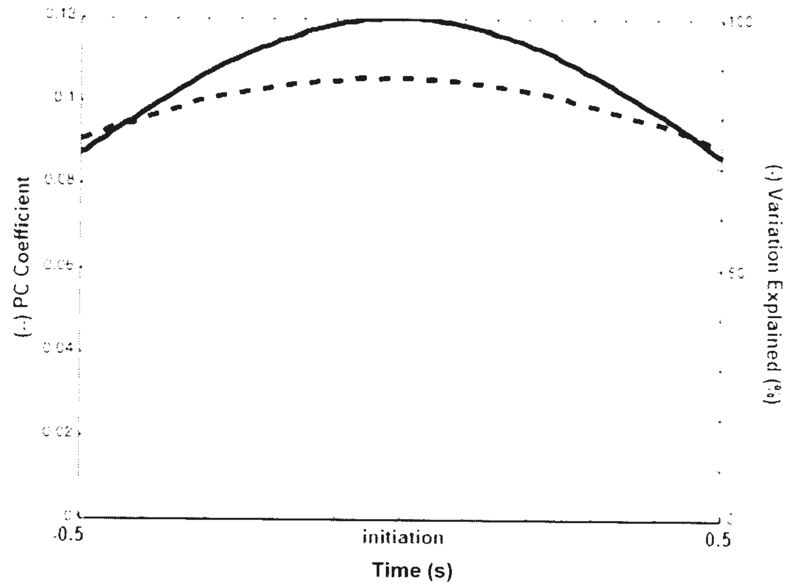


Figure 4.4: (a) The original coefficient of the 2nd component of roll during backwards stepping (- - -) and the coefficients scaled to the percentage of the variation explained (-). (b) Reconstructed waveforms during MIIs and MICs indicated from the 2nd principal component scores to be a difference operator.



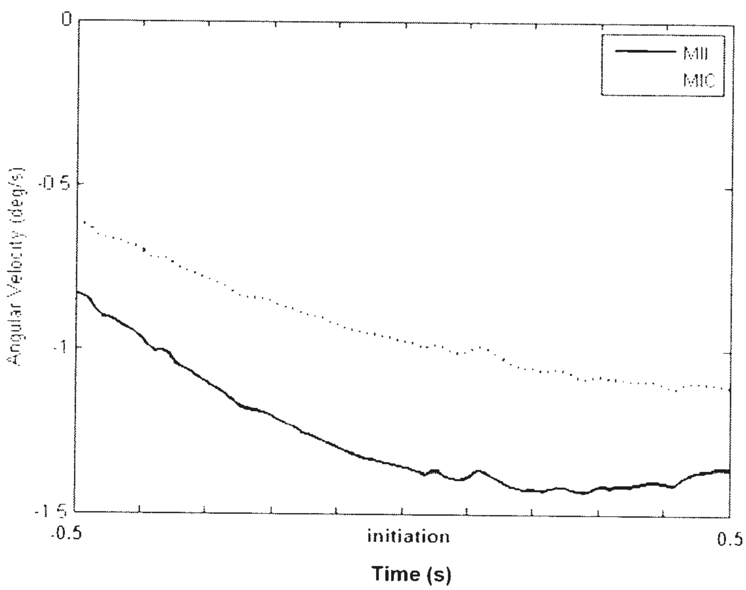


Figure 4.5:(a) The original coefficient of the 1st component of pitch during forwards stepping (- - -) and the coefficients scaled to the percentage of the variation explained (-). (b) Reconstructed waveforms during MIIs and MICs indicated from the 1st principal component scores to be a magnitude operator.

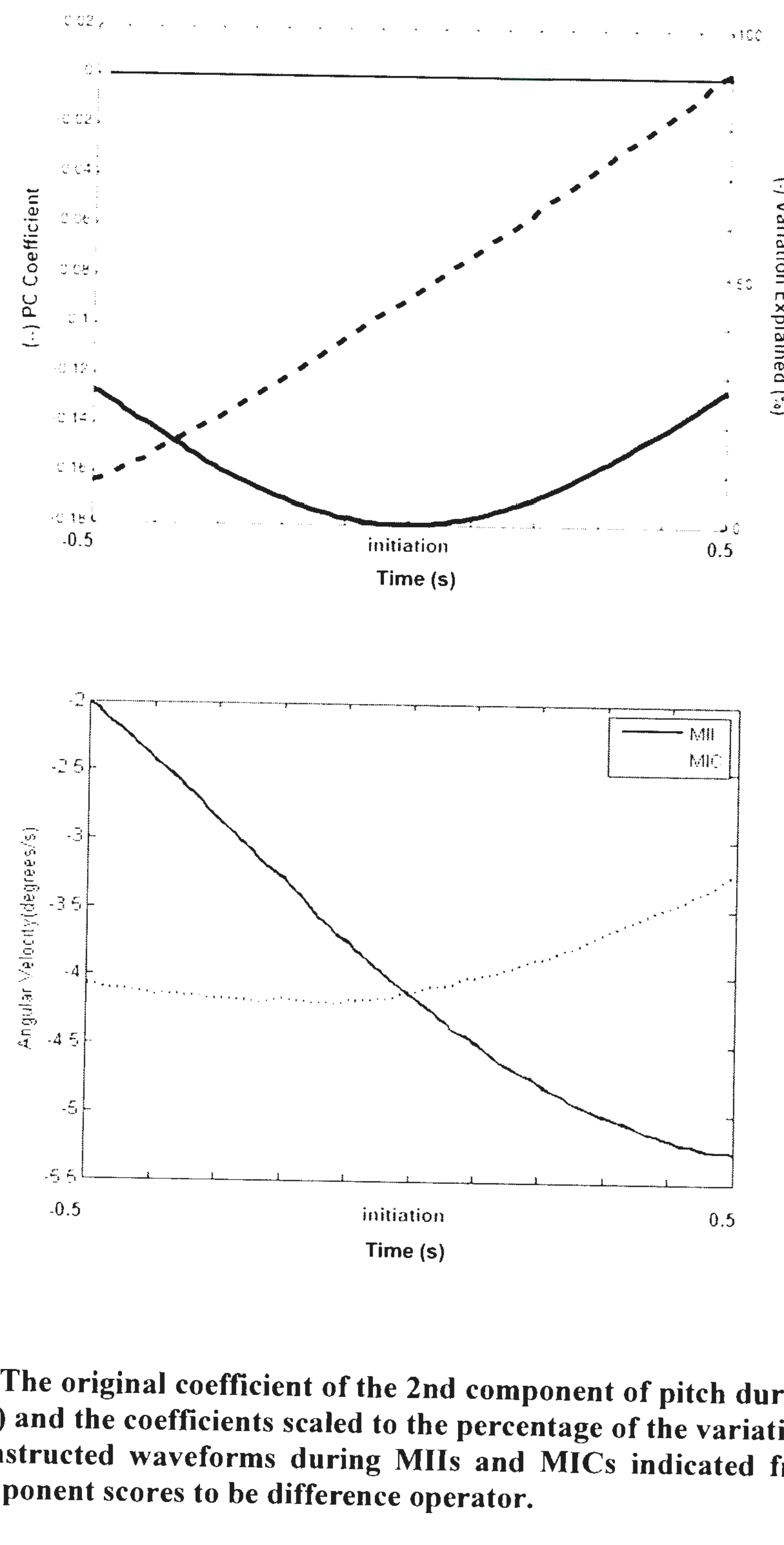
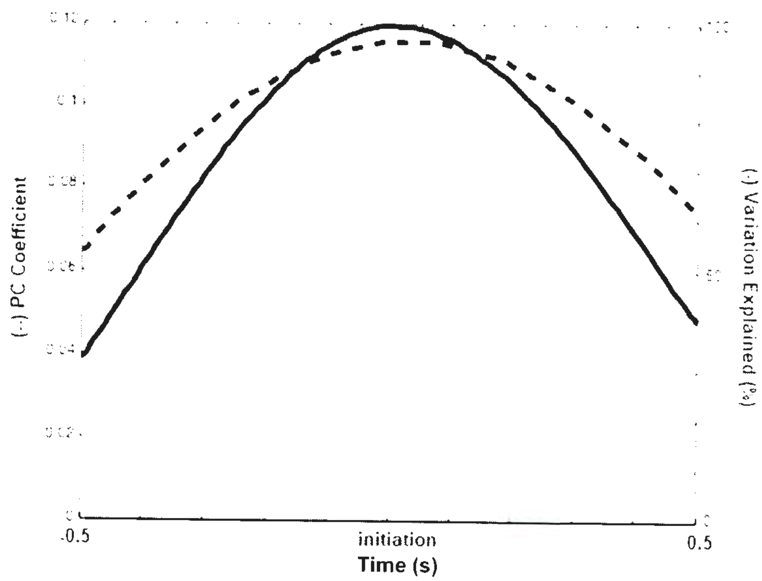


Figure 4.6(a) The original coefficient of the 2nd component of pitch during forwards stepping (- - -) and the coefficients scaled to the percentage of the variation explained (-). (b) Reconstructed waveforms during MIIs and MICs indicated from the 2nd principal component scores to be difference operator.



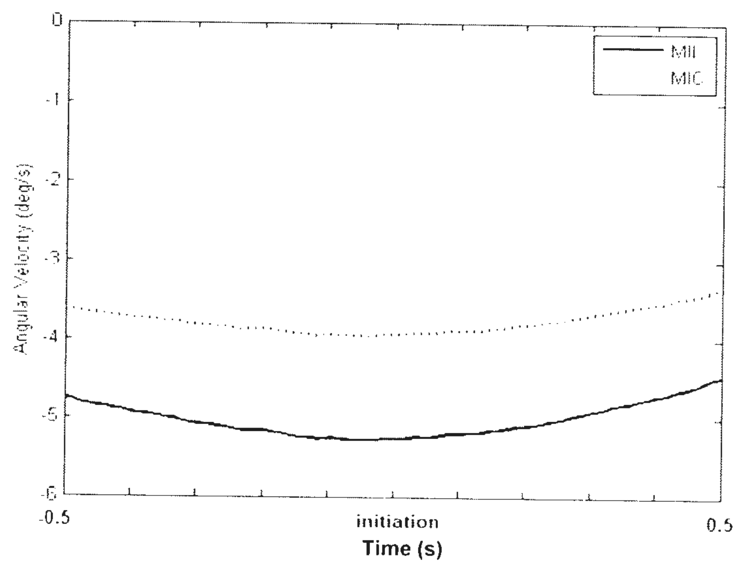
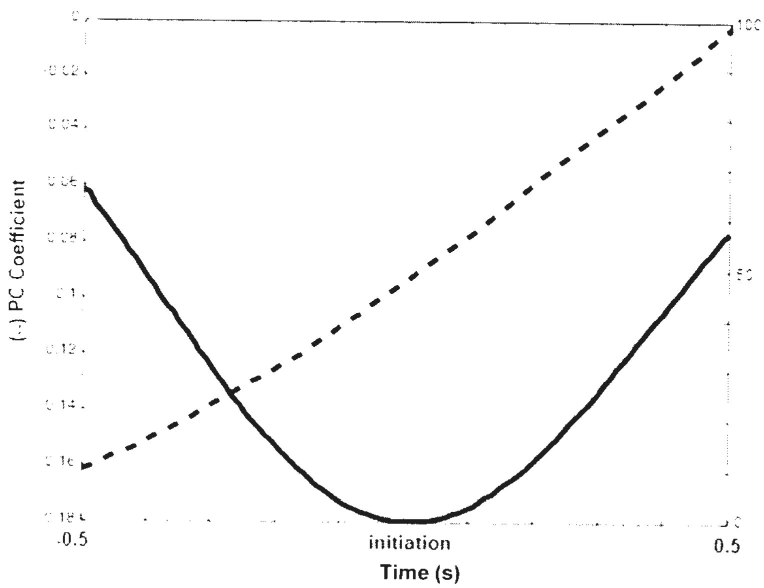


Figure 4.7: (a) The original coefficient of the 1st component of roll during forwards stepping (- - -) and the coefficients scaled to the percentage of the variation explained (-). (b) Reconstructed waveforms during MIIs and MICs indicated from the 1st principal component scores to be a magnitude operator.



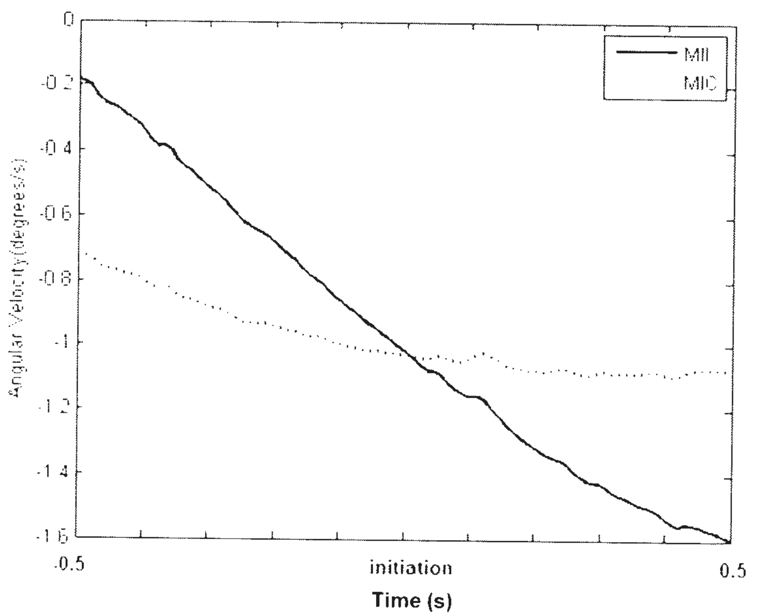


Figure 4.8: (a) The original coefficient of the 2 nd component of roll during backwards stepping (- - -) and the coefficients scaled to the percentage of the variation explained (-). (b) Reconstructed waveforms during MIIs and MICs indicated from the 2nd principal component scores to be a difference operator.

4.5 DISCUSSION

PCA allows for the identification of the portions of the motion responsible for the greatest amount of variability and partitions the variability into uncorrelated components instead of using predetermined factors (Wrigley et al., 2006). Previous studies have found that PCA can detect slight changes in waveform shape between groups through the analysis of modes of variation, to explore and explain specific patterns within a group of variables (Deluzio et al., 1997). As a result, PCA can sometimes identify differences that cannot always be identified using parameter based analysis (Wrigley et al., 2006). Initial parameter based analysis of the mean and peak motions at MII and MIC discussed in *Chapter 3* revealed that while MICs occurred more frequently than MIIs there were no significant differences between the amplitudes of the motions that initiate these postural responses. Further analysis of the platform motion waveforms using PCA has revealed that there are distinct quantifiable differences between MIIs and MICs. These results further confirm the idea that there are distinct differences between the events that cause stepping when people are constrained to one particular stance compared to those when people are allowed to move their feet as they require to maintain balance, and cannot be considered the same event when examining postural response to moving environments from either a biomechanical, or ship operability standpoint.

For both pitch and roll directions the majority of the variability could be described by two components of which the 1st component, a magnitude operator, was statistically significant in the pitch direction only. This magnitude operator, which accounts for 80-

90% of the variability, clearly suggests that the amplitudes of the platform motions that are required to initiate MIIs are greater than those required to initiate MICs. Statistically significant differences found only in pitch direction were likely due to the larger differences in platform kinematics between MIIs and MICs in the pitch direction when compared to the roll direction. The lack of significance found between MIIs and MICs for the second component for pitch and roll in all instances may be related to the small proportional of variability explained by this component. These results support the idea that MIIs and MICs are clearly distinct events that are initiated by different wave-induced platform motion characteristics. As thus, when examining and modeling postural response to wave-induced platform motions all stepping responses cannot be categorized as the same type of event, and differences in their initiation characteristics must be considered.

Initially it was hypothesized that due to the cyclic nature of wave-induced platform motions participants may use MICs as anticipatory reactions to minimize the destabilizing effects of an upcoming perturbation, whereas MIIs are used as reactive mechanisms once it has been determined that all fixed-support postural stabilizing mechanisms have been exhausted. To the authors' knowledge examination of this hypothesis using traditional summary measures and parametric analysis has not been performed. Unlike summary measures (e.g. mean and peaks) PCA allows for the temporal characteristics of the trajectory of a variable to be maintained (Wrigley et al., 2005). Preservation of these temporal characteristics is important in circumstances, such as this study, where it is believed that the effect of independent variable (i.e. platform perturbations) on the dependent variable (i.e. MIIs and MICs) can potentially change over time. Examination of the velocity loading curves of the first principal component reveals that while the component has a large effect throughout the whole MII or MIC event it is greatest at the time of initiation. Therefore, MII and MIC are most often reactive in nature. Stepping is initiated as a response to an immediately perceived motion, instead of in anticipation an upcoming event. This supports the idea of a tradeoff between speed of the compensatory reaction and the stability of the resulting step with the one that maximizes dynamic stability being chosen. Environmental constraints affect the length of change-in-support reaction by changing the length of the anticipatory postural adjustment to insure that lateral stability is maintained (Maki and McIlroy, 2003). While cyclic in nature, the combined effects of unique motions in all six degrees of freedom may make it difficult to accurately predict magnitude and direction of the upcoming perturbation to a degree necessary to make a successful postural adjustment, without potentially placing the body in greater risk of upcoming perturbation in a different direction. Stepping forwards or backwards increases the size of the base of support (BoS) anterior-posteriorly in response to perturbations in the pitch or surge degrees of freedom. However, depending on the size of the step, the size of the BoS may decrease in the medial-lateral direction, in turn, decreasing lateral stability and thus increasing susceptibility to roll perturbations. The lateral weight shift to the support leg during stepping also decreases lateral stability (Maki et al. 1993). Therefore, if the subject is not completely sure of the nature of the upcoming perturbations it may be more beneficial for them to not make a postural adjustment too far in advance.

Though the idea of MICs differs from the current definition of a MII, it may help explain much of the variability in MII occurrence seen in experimental trials. The current definition of a MII was defined when it was believed that change-in-support mechanisms were used only after the limits of fixed-support mechanisms had been reached. Therefore, thresholds of these reactions could be defined by clear physics-based postural stability limits. Since the creation of this MII definition, postural stability research in the areas of biomechanics and motor control have since proven that response choice is not only based upon stability limits, and that other factors affect response choice (Maki & McIlroy, 1997). These factors may include: biomechanical task constraints, movement strategies, the sensory environment, postural orientation, dynamics of control, cognitive resources, experience and practice, and perception of the goal and its context (Horak, 2006).

For the purpose of this study pitch and roll platform motions during forwards and backwards MIIs and MICs were examined. While in all cases most of the variability could be described by two principal components, with the first component being a magnitude modifier accounting for most of the variability, only the first component while stepping backwards was significantly different between MIIs and MICs. Anatomical characteristics of the body and their effect on postural responses to perturbation may account for these results. The anatomical nature of the foot results in different responses between forwards and backwards stepping. During perturbations that initiate forwards stepping the flexibility of the toes and resultant rising onto the toes in response to the perturbation before stepping affects stepping occurrence (McIlroy & Maki, 1993). This reaction is not possible when being exposed to perturbations that initiate backwards stepping, and thus may result in more variability that prevents significant differences between MIIs and MICs.

Motions about the roll axis result in lateral destabilization of the human body. The shape of the BoS in the posture used in this study and anatomical nature of the body makes the body more stable in the medial-lateral direction. Maki and colleagues (1997) found that due to anatomical constraints of the foot and ankle change-in-support reactions as a result of lateral perturbations are far more complex than anterior-posterior change-in-support reactions. These differences include more rapid, foot-lift, more complex swing trajectory and increases in swing leg duration, making lateral change-in-support reactions less favourable than anterior-posterior ones. Perturbations in the roll directions may have less of an influence on MII and MIC initiation, and therefore differences between MIIs and MICs in the roll direction may not be significant.

Research has determined that there is a significant relationship between centre of mass (CoM) dynamics and stability. It has been suggested that in order to accurately predict change-in-support mechanisms (i.e. MIIs and MICs) body momentum must be considered (Maki and McIlroy, 2003). Due to equipment and laboratory limitations it was only possible to measure platform motions and occurrence of MIIs and MICs from video analysis, and measurement of whole body kinematics and kinetics and calculation of CoM was not possible. Differences between MIIs and MICs may be related to CoM placement and momentum. Therefore, in order to gain a greater understanding in the differences between MIIs and MICs, CoM dynamics and their relationship with platform perturbation characteristics at the time of change-in-support reaction initiation should be considered.

Differences between MIIs and MICs may be also more apparent when examined from a neuromuscular standpoint. It was previously hypothesized that MIIs may be a reactive mechanism while MIC may be preventative mechanism. Examination of platform motion waveform characteristics time at stepping initiation suggests that both MIIs and MICs are reactive in nature. However, neuromuscular differences between events still may be possible. Examination of neuromuscular activation patterns before and during initiation of MII and MIC would help further explore the differences between these events.

Using physics-based calculations to determine the tip coefficients that would result in the initiation of a change-in-support reaction assumes that stepping occurs only once all fixed support strategies have been exhausted and does not consider that using a change-in-support mechanism may be more beneficial than a fixed support reaction in some circumstances. To the authors' knowledge previous work involving MIIs have conformed to this definition by asking subjects to maintain a standardized posture unless stepping is absolutely necessary to maintain balance. Participants were asked to display postural responses that may not necessarily be how they would naturally perform if allowed to use any support postural strategy. The unconstrained standing task that is representative of an MIC used in this study attempts to mimic the natural response that would be used in offshore environments. Therefore, it is plausible that postural responses used naturally while working in moving environments may be MICs.

4.7 CONCLUSION

Results of this research study have shown:

1. that differences in MIIs are MICs are quantifiable and can be described in PCA by two distinct modes of variation.
2. most variation is related to the magnitude of the platform perturbation waveforms that cause their initiation.
3. MIIs and MICs are distinctly different events that are caused by significantly different platform motions.

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CHAPTER 5: ON THE RELATIONSHIP BETWEEN SHIP DECK MOTIONS AND INITIATION THRESHOLDS FOR HUMAN MOTION INDUCED CORRECTIONS

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5.1 ABSTRACT

The purpose of this research was to quantify the magnitude of multi-directional wave-induced platform motions and the requirement to adjust foot positions in order to maintain stability. This foot correction strategy has been termed a motion induced correction (MIC). Twenty-four participants (12 male and 12 female) with limited experience in offshore environments performed two stationary standing tasks and two manual materials handling tasks while being exposed to simulated deck motions that varied in waveform amplitude. MICs were noted and corresponding platform motion characteristics were recorded. Results show that MIC initiation and corresponding platform velocities and accelerations were highly variable between participants, however, when grouped by direction of stepping a clear relationship between pitch kinematics and MIC initiation was apparent. These results further support the premise that postural response in offshore environments is a complex mechanism that is highly variable and while platform kinematics heavily affect response other factors may also be influential. Naval architects and personnel concerned with safety still require motion thresholds that will likely induce postural instability while taking into account other factors that may, in conjunction with perturbation magnitude, define the variability of the complex postural response mechanism.

5.2 INTRODUCTION

With two thirds of a human's mass positioned above the lower extremities, bipedal stance is naturally unstable. Balance, also referred to as postural stability, equilibrium and postural control, is a complex motor skill that describes the dynamics of body posture used in preventing falling (Punakallio, 2005). From a biomechanical perspective, postural stability is related to the inertial characteristics of the body's segments and external forces acting upon these segments. External perturbations compromise the body's ability to maintain postural equilibrium. Postural responses to these external perturbations use a combination of feedforward and feedback control loops to maintain dynamic equilibrium while performing a task. Predictive (anticipatory) feedforward mechanisms are most predominant when upcoming perturbations are predictable; while reactive (compensatory) mechanisms are more central in unpredictable environments where there is little or no time to prepare for the oncoming perturbation (Maki & McIlroy, 1997). As a result, a variety of unique motor control strategies can be used to maintain postural stability.

Offshore wave-induced platform motions are comprised of perturbations in six degrees of freedom. It cannot be assumed that each direction of motion has an equal effect on response choice when presented as a multidirectional perturbation. The continuous multi-directional nature of platform perturbations further increases the complexity of predicting postural response. The asymmetric non-rigid design of the human body causes the contributions from sensory systems and resultant neuromuscular responses to multidirectional perturbations to differ from unidirectional translational and rotational perturbations (Carpenter & Allum, 1999; Carpenter et al., 2001; Preuss & Fung, 2007). The complexity of multi-directional perturbations also results in increased variability of postural synergy groupings during fixed-support reactions, which, in turn, further increases the variability of the response choice (Henry et al., 1998). The resultant postural response is non-linear in nature. Increases in external stimuli (e.g. size of the perturbations) are not, necessarily, proportional response gain. However, difficulties with stimulus-response measurement and inherent variation in responses within and between persons limit the current understanding of the relationship between stimuli and response (Maurer et al. 2006).

Clinical biomechanics and motor control research has examined human postural response to unstable surfaces and external perturbations. However, there is limited research that examines the effects of moving environments (e.g., marine environments) on postural responses. Marine environments pose some unique conditions that can potentially increase the challenge of maintaining balance (Wertheim, 1998). Within nautical engineering literature, the effects of platform motions on human postural stability have been studied from a ship operability or habitability perspective. This literature suggests that there are specific events that pose the greatest challenges to postural stability. These events, known as motion induced interruptions (MIIs), are incidents where the acceleration due to ship motions become sufficiently large to cause a person to slide or lose balance unless they temporarily abandon their allotted task to make a postural adjustment in order to remain upright (Crossland & Rich, 1998). The most common type of MII is a change-in-support reaction to change the size or shape of the base of support (BoS) in response to a momentary loss of postural stability (Stevens & Parsons, 2002; Baitis et al., 1995).

In the nautical engineering community, physics based modeling approaches have been used to predict MII occurrence or frequency by examining the relative instability of the person in a moving environment while performing a particular task (Graham, 1990; Wedge & Langlois, 2003). These models were originally developed to estimate how vessel design and operational demands affect the stability of a "standard" person and were more concerned with vessel performance and design than operator safety (Crossland & Rich, 1998; Crossland et al., 2007; Langlois et al., 2009; Baitis et al., 1995). These models, neglect human responses related to postural control and, the variability in the manner in which humans obtain, maintain, or regain postural stability. The variability in human responses complicate the association between physics-based predictions and outcome operator performance, It has been suggested that including elements of human cognition and abilities to react to perturbations within these models , in addition to basic system dynamics would improve the overall ecological validity of this approach (Langlois et al., 2009).

Current thinking regarding MIIs assumes all corrective foot actions (i.e., moving of the feet) that a person makes are adaptations to maintain postural stability after all efforts to maintain a fixed- foot support have been exhausted. Previous research suggests change-in-support reactions occur well before stability limits are reached, and, do not fit the current definition of an MII (Langlois, 2009). These events, which can be defined as motion induced corrections (MIC) occur more frequently and initiate following lesser perturbations than those which initiate MIIs. Though this idea of MICs may identify a different phenomenon than current MII modeling, it will help explain much of the variability in MII occurrence seen in experimental trials.

Additionally, current MII prediction models typically describe stationary standing activities and thus have limited applications in real work environments where workers generally perform a large variety of tasks. When a person performs a manual materials handling (MMH) task the centre of mass (CoM) is shifted and balance is disturbed. In response to this disturbance the person must make postural adaptations to maintain stability and balance. Postural responses are task dependent, and the effects of moving environments on balance may potentially differ between tasks. Previous work has found the human postural response to unidirectional and multidirectional platform motions differs between types of MMH activities. The same modeling assumptions and parameters used for standing are not valid for all occupational demands and any prediction models must be task dependent (Matthews et al., 2007; Holmes et al., 2008; Duncan et al., 2007).

To improve upon the current understanding of the mechanisms related to the maintenance of postural stability in motion-rich environments there must be a better understanding of the effects of multidirectional perturbation characteristics on response choice and potential response thresholds. Using an empirical approach, the relationship between platform perturbation magnitudes and MIC initiation can be examined. This experimental approach allows for the assessment of various work-related tasks that not generally considered in traditional models and may potentially produce results that can be used validity in the naval architecture and engineering communities to help inform the models' ecological validity. These improved models could be used to develop more effective interventions to prevent motion related injuries and provide better information about ship design and workstation outcomes. Hence, the purposes of this study were to examine the relationship between platform perturbation kinematics determine if a threshold based upon perturbation kinematics for MIC initiation exists.

5.3 METHODOLOGY

5.3.1 Participants

Twelve males and twelve females (age: 28.32 ± 5.78 years; stature: 173.35 cm ± 7.16 cm; mass 74.48kg ± 13.32 kg) performed two stationary standing and two MMH tasks on a six degrees of freedom motion platform while being exposed to five simulated offshore motion conditions. Participants were recruited from a university population, had little to no experience working in moving environments, were not susceptible to motion sickness, and free of any known musculoskeletal injuries. Prior to commencing the study all participants were presented with documentation outlining the study and were given the opportunity to ask questions about the research before signing the consent form. This study was approved by the Human Investigations Committee of Memorial University of Newfoundland.

5.3.2 Procedures

Two standing tasks and two MMH tasks were performed in a simulated moving environment. The first task involved participants standing with feet shoulder width apart in parallel stance. During the second task participants stood with feet in a tandem stance. Each task was performed for five minutes in each of the five distinct motion conditions with a period of 5-10 minutes rest between each trial. All motion trials were performed over two, two and a half hour sessions. During each session two of the four tasks were performed in all five motion conditions for a total of ten motion trials per session. Motions and tasks were randomized to limit potential learning and/or fatigue effects.

The two stances chosen were representative of two fixed support stances commonly used in response to wave induced platform perturbations but differed in stance configuration. During the parallel stance standing task, participants were asked to stand with their feet shoulder width apart thus extending their base of support (BoS) in the medial-lateral direction *(Figure 5.1(a))*. While performing the tandem stance standing task, participants stood with their feet shoulder width apart with their right foot anterior of midline and their left foot posterior of midline, thus extending their BoS in the anterior-posterior direction *(Figure 5.1 (b))*. To simulate realistic conditions, participants were asked to move their feet whenever necessary to maintain balance. All foot movement events were considered to be MICs. The MMH tasks performed were a stationary and a sagittal lifting/lowering task. During the stationary holding task the subject was asked to hold a 10kg load in a "dead lift" posture with feet shoulder width apart, elbows fully extended straight and the load held as close to the individual as possible *(Figure 5.2)*. During the lifting/lowering task motion profiles, subjects lifted and lowered the same 10kg load directly to and from a shelf 72cm high and 60cm in front of them *(Figure 5.3)*. Lifts and lowers were performed at a rate of 3 lifts/minute and 3 lowers/minutes (i.e. six manipulations per minute) and performed using a two-handed freestyle lifting technique. While these are common tasks and require no training to gain expertise, they may not be part of regular daily/occupational activities. The weight of the load was chosen to simulate a typical load that would be lifted on marine fishing vessels and for comparison purposes to other studies. All lifts and hold met the safe lifting guidelines outlined by the National Institute for Occupational Safety and Health (NIOSH, 1981). Audio cues were used to indicate to the participant when to start lifting or lowering. To ensure the participant remained in the same position throughout the task they were asked to keep (or reposition) their toes on a line measured 60cm from the shelf prior to the start of each load manipulation. To aid in accurate box placement during the task, an origin and destination were clearly marked on the floor and surface of the shelf. All tasks were performed with the participants facing the bow of the motion platform. While performing activities the participant was told to move their feet as desired, whenever it was felt necessary to maintain balance. Foot positions were marked on the floor of the motion platform so subjects could return to the standardized position after initiation of an MIC.

The four tasks were performed on a Moog 6DOF2000E electric motion platform (Moog Inc. East Aurora, New York). Simultaneous periodic ship motion in five of the six available degrees was simulated based on time series data collected in a previous research program that examined the deck motion of fishing vessels of various sizes. Yaw was not introduced within the motion profiles due to the small amplitudes relative to the other angular motions under typical conditions.

The motion applied to the platform was based on the profiles for the five degrees of freedom listed in Appendix B. These profiles are considered to include at least one threshold for MIC initiation for any participant, as tested in pilot work. In the present work the conditions used were somewhat more severe that these profiles through the application of an amplification factor to the pitch and roll profiles, to set the severity of the condition selected for the trial. Five conditions of increasing severity from Condition

1 to Condition 5 were defined by the amplification factors for pitch and roll of 1.75, 1.875, 2.0, 2.125, and 2,25, respectively. Other than the amplification factor applied to (only) pitch and roll, the same sequences of displacement amplitudes versus time, as listed in Appendix B, were used in each trial repeated with the same severity condition.

A canopy was placed over the motion platform to limit the effect of earth referenced visual cues. During all trials the participants faced the bow of the motion platform.

Figure 5.1: Parallel Standing

Figure 5.2: Tandem Standing

Figure 5.3: Stationary Holding Task

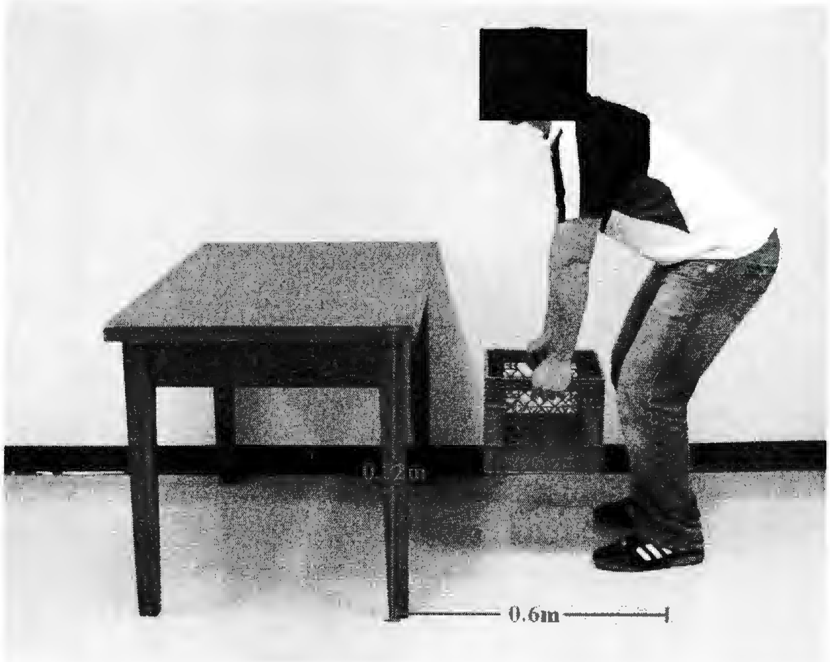

Figure 5.4: Sagittal Lifting/Lowering Task

5.3.3 Data and Statistical Analysis

Motion trials were videotaped at 60Hz and MIC initiation and direction of the event (i.e., forwards or backwards) and the event characteristics were later determined from video recordings of the trials. Video was synchronized with profiles using visual cues. An MIC was considered to be any instance when the subject stepped from their original position or grabbed the guard rail during the trial. Any stepping motion performed within one second of another was considered to be part of the previous MIC. This one second time envelope was determined through the examination of recovery times following MIC events during pilot work to be the time required to ensure that any stepping was in response to the current perturbation and not the previous MIC.

Based on the results of the *Experiment* 1 which suggested that MICs are reactive in nature, platform kinematics at the time of initiation were examined. MIC initiation event occurrences were plotted versus time for each participant. Plots for each participant were compared using visual inspection to determine if a relationship between profile time and MIC initiation existed. Platform velocities and accelerations at the time of MIC initiation were calculated from the linear equations governing the motion profiles. The motion curves associated with the MICs from all motion conditions were grouped and examined as a whole to determine if there was range of kinematic values at which MICs occurred more frequently. The frequency of platform velocities and accelerations experienced at the time of MIC initiation and equal sized groups of instances when no MICs took place were plotted as frequency distributions and compared. This equal sized group of instances was randomly selected from all events where no MICs took place. Significance of these relationships was determined using independent *t*-tests.

5.4 RESULTS

5.4.1 Time of MIC Event Initiation

Number of MICs of all participants together for each task across all motion conditions were grouped and examined as a whole *(Table 5.1)*. MIC occurrence was greatest for tandem standing and lowest for the lift/lower task. For all tasks backwards stepping MICs occurred more frequently.

Table 5.1: MIC occurrence for all tasks

	Parallel	**Tandem**	**Hold**	**Lift/Lower**
Backwards	221	318	123	87
Forwards	164	132	42	50
Total	**385**	**450**	**165**	**137**

Figure 5.5 Depicts an example of the distribution of MIC events for participants over the course of parallel standing during condition 5. Examination of the timing of the MIC indicates that while there are instances where multiple participants stepped, much of MICs initiation is quite variable between participants. Similar distributions were seen for all tasks.

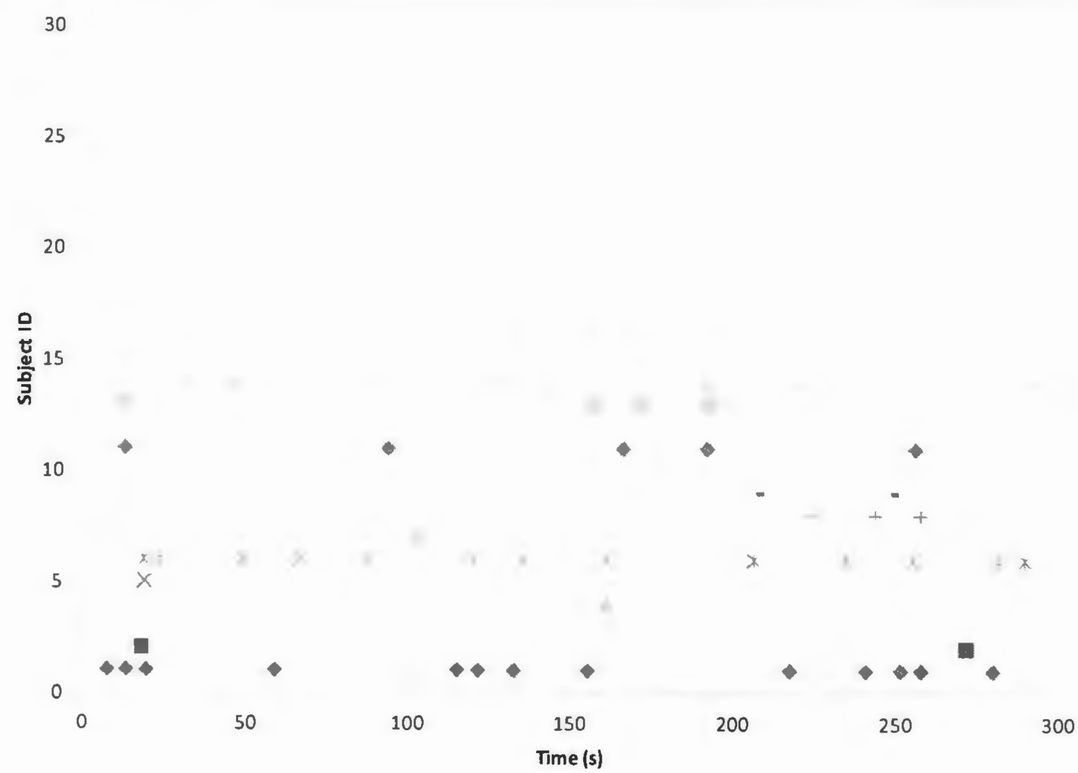

Figure 5.5: MIC occurrence while standing parallel during condition 5. Plotting time of MIC occurrence by participant shows the between subject variability during the trials.

5.4.2 MIC Kinematic Frequency Distribution

Frequency distributions of the velocities and accelerations in the pitch and roll directions at the time of MICs initiation were examined for all five motion profiles to determine if there was a relationship between any of the platform motion characteristics and MIC initiation. Figure 5.6 depicts the frequency distribution with respect to pitch acceleration while standing. Similar distributions were seen for the pitch acceleration of all tasks.

Evaluations of these plots show that for all tasks plots are bimodal with similar values of kurtosis *(Table 5.2)*. Due to the fact that normality of the data could not be assumed non-parametric Mann Whitney U tests were used. Results of these test suggest that there are only significant differences in pitch acceleration between MIC initiation and non-MIC events of the motion profile *($p < 0.05$) (Table 5.3)*. Therefore for the purpose of clarity only results of pitch accelerations will be discussed

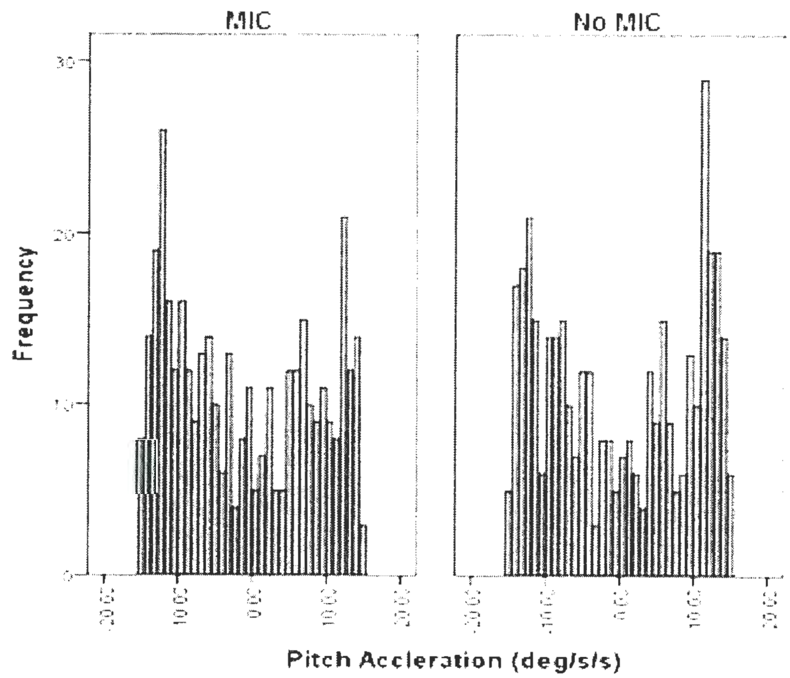

Figure 5.6: A comparison of pitch acceleration at the time of MIC initiation frequency distributions during parallel standing to no-MIC events

Table 5.2: A comparison of skewness and kurtosis of all MICs versus no-MIC events by task

	Skewness		**Kurtosis**	
	MIC	**No MIC**	**MIC**	**No MIC**
Stand	.198	-.039	-1.309	-1.530
Tandem	.381	-.040	-1.358	-1.501
Hold	-.196	.124	-1.256	-1.553
Lift	.411	.097	-1.286	-1.494

Table 5.3: Differences in mean pitch acceleration (deg/s/s) at MIC initiation when compared to non-MIC times p<0.05 = significance.

	Parallel	**Tandem**	**Hold**	**Lift**
MIC	-1.01(8.14)	-1.76(8.45)	-1.72(8.80)	-2.20(8.43)
No MIC	0.03(8.45)	0.03(8.45)	-4.44(8.82)	-0.73(8.56)
p-value	*0.037*	0.782	0.351	0.728

MICs were also grouped and analyzed based on direction of stepping (i.e. forwards and backwards). Due to the low occurrence of forwards stepping for holding and lifting tasks MICs performed only on backwards stepping events were included. Evaluations of skewness. kurtosis of the pitch acceleration and velocity frequency plots reveal differences between MIC and no MIC events *(Figures 5.7 and 5.8)*. *T*-tests revealed significant differences between MIC and no MIC event for pitch accelerations and velocities for all tasks *(Table 5.5)*. Therefore, for brevity only frequency plots for these kinematic variables will be displayed

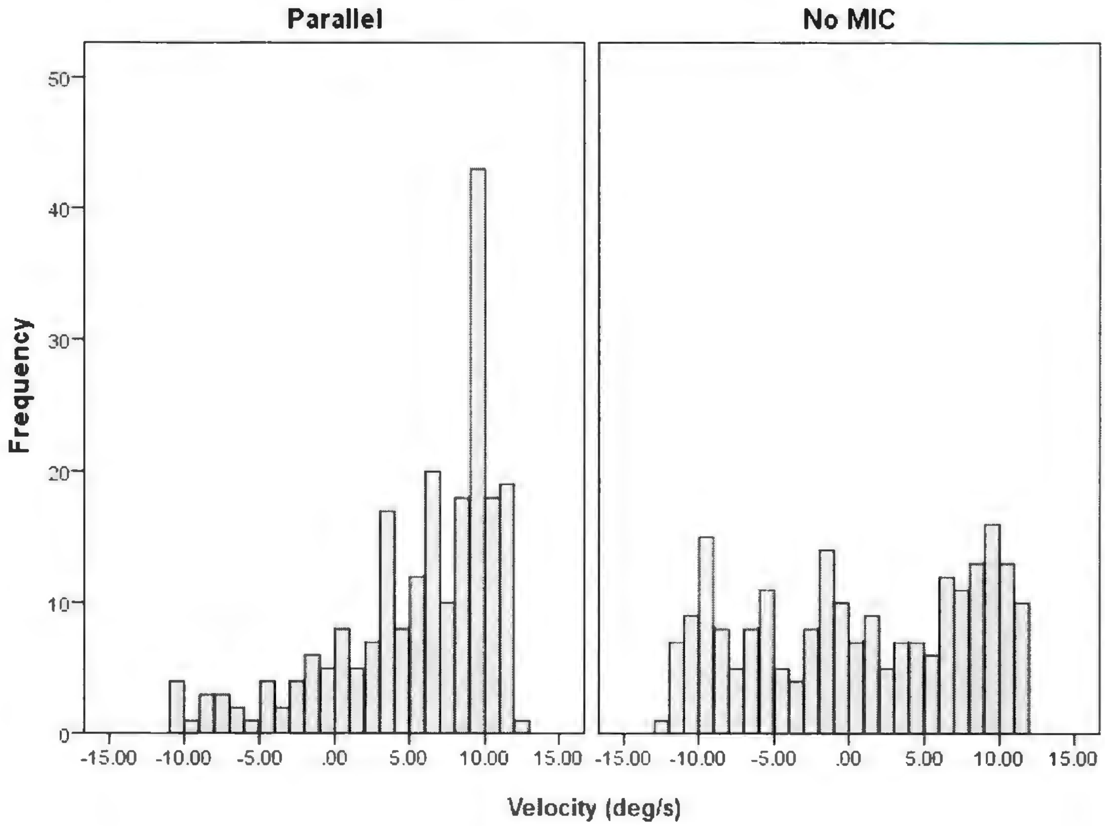

Figure 5.7: A comparison of pitch velocity at the time of backwards stepping MIC initiation frequency distributions during parallel standing to no-MIC events

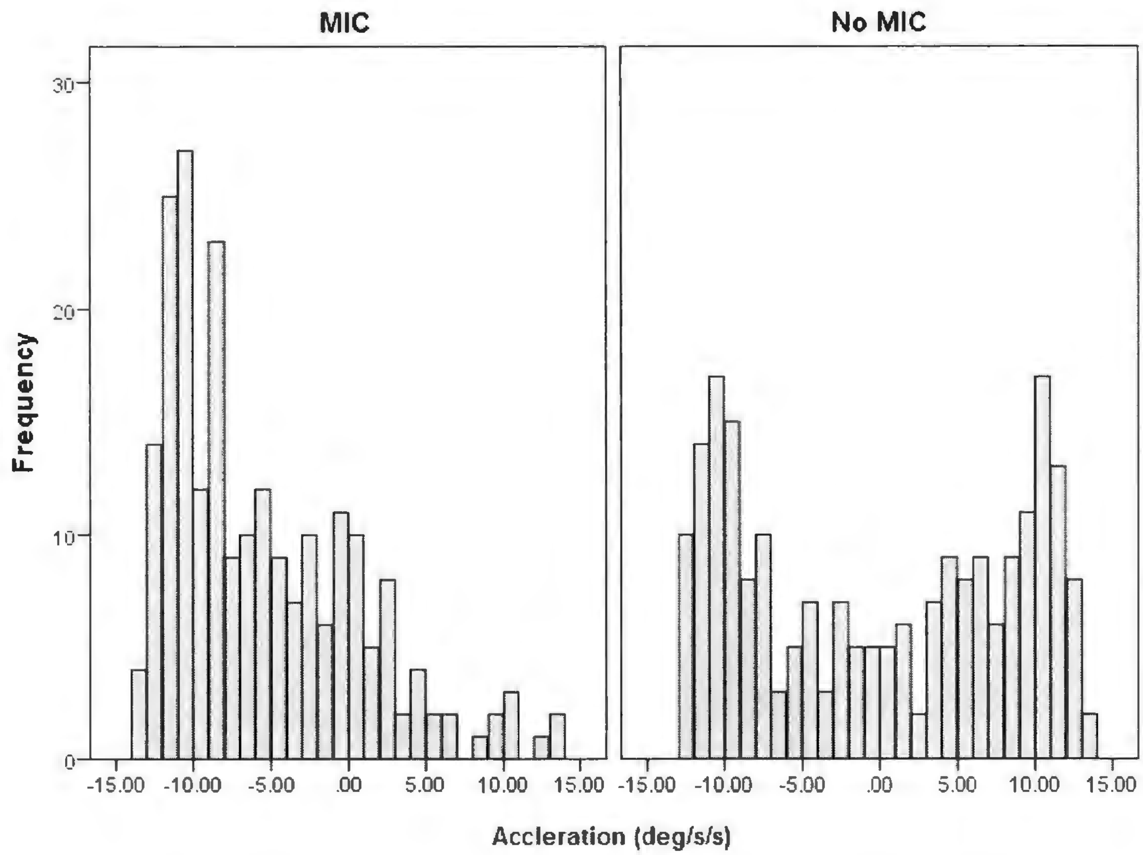

Figure 5.8: A comparison of pitch acceleration at the time of backwards stepping MIC initiation frequency distributions during parallel standing to no-MIC events

Table 5.4: A comparison of skewness and kurtosis of all backwards stepping MICs versus no-MIC events by task

	Velocity				Acceleration			
	Skewness		Kurtosis		Skewness		Kurtosis	
	MIC	No MIC	MIC	No MIC	MIC	No MIC	MIC	No MIC
Stand	-1.151	-.137	.649	-1.320	.960	-.020	.351	-1.544
Tandem	-.821	.063	-.522	-1.456	.968	-.055	-.111	-1.492
Hold	-.891	.144	.043	-1.329	1.150	-.001	.413	-1.558
Lift	-.377	.083	-.991	-1.421	1.560	-.298	2.054	-1.332

Table 5.5: Mean MIC initiation and no MIC pitch accelerations and velocities (p<0.05 = significance).

	Parallel		Tandem		Hold		Lift	
	Vel. (deg/s)	**Accel. (deg/s/s)**	**Vel. (deg/s)**	**Accel. (deg/s/s)**	**Vel. (deg/s)**	**Accel. (deg/s/s)**	**Vel. (deg/s)**	**Accel. (deg/s/s)**
MIC	5.47 (5.43)	-5.58 (6.05)	3.93 (6.66)	-4.87 (6.79)	4.36 (5.81)	-5.98 (6.61)	3.33 (6.04)	-7.02 (5.96)
No MIC	0.73 (7.31)	0.00 (8.61)	-0.41 (7.68)	0.04 (8.41)	-0.89 (7.20)	-0.03 (8.91)	-0.44 (7.63)	1.49 (8.32)
p-value	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*

5.5 DISCUSSION

Maintaining postural stability is a complex process. Difficulties with stimulus/response measurement and inherent variation in responses within and between persons limit the current understanding and estimation of threshold values (Maurer et al. 2006). Within the naval architecture and engineering communities attempts have been made to predict the stimulus thresholds of wave induced platform perturbations that would induce MIIs (Graham, 1990; Wedge & Langlois, 2003). It has been recommended that a systematic examination of the effects of possible components of wave-induced platform perturbations, including amplitude, frequency and predictability of lateral and vertical accelerations, on postural stability and response choice is needed to improve the current MII models (Lewis and Griffin, 1997). However, to the authors' knowledge these assumptions in regards to platform perturbations have never been quantitatively verified. This research is an attempt to examine the empirical relationships between perturbation amplitude and stepping. While taking into consideration the variability associated with response choice, the researchers attempted to examine the potential range of platform kinematics associated with MIC initiation. Results of this study reveal a relationship between MICs and platform kinematics when MICs are grouped by direction of stepping.

Previous work that examined MIIs did not classify events based on direction of stepping (Matthews et al., 2007; Holmes et al., 2008; Duncan et al., 2007). However, postural response literature suggests that change-in-support responses such as MIIs and MICs are directionally dependent (Maki & Milroy, 1997) and therefore, the motions which cause forwards and backwards stepping MIIs or MICs in moving environments would be different. In this current research, analysis of all MICs, regardless of direction, yielded no visible trend in platform kinematic frequencies at the time of event initiation, and only significant differences in pitch platform accelerations. Further analysis involving the grouping of MIC events by direction of stepping revealed clear trends of increasing MIC initiation when compared to non-MIC events were present. This suggests that, while MIC initiation is still highly variable, when direction is taken into account, a kinematics/initiation relationship may be present. While MICs did occur throughout a similar range of platform kinematics as that in which no MICs occurred the frequency of MIC occurrence displays a non-linear increase with increased platform amplitude. These results further enforce the idea that forwards and backwards stepping MICs are caused by different platform kinematics. As expected, forward stepping MIC events occur less frequently and are most often produced by positive pitch accelerations, while backwards stepping events are more frequently a result of negative pitch accelerations.

Previous research in moving environments has suggested magnitude and predominate direction of the motion have a significant effect on MII initiation. Duncan et al. (2010) found that incidence of MII while standing increased with increased motion conditions. This was accompanied by increases in thoraco-lumbar velocities and CoP changes when compared to non-MII events. Although platform motions at the initiation of the MII events were not examined by Duncan et al.(2010), it was thought that the motions causing the events would also be significantly greater. In this present analysis platform velocities and accelerations at the time of MIC initiation were also compared to non-MIC events.

Significant differences in backwards stepping MIC initiation platform kinematics when compared to non-MICs were found only for pitch acceleration and velocity for all tasks *(see Table 5.3)*. Additionally, significant differences in roll velocities and accelerations were found between MICs and non-MICs while standing in tandem stance. These results suggest that directional effects in MIC response may be task dependent. Further examination of this relationship between task and MIC is presented in *Chapter 7*.

Even once MICs were grouped by direction of events large amounts of variability were still present. Participants did not consistently perform MICs when expected and would often perform an MIC at a lower amplitude after successfully using a fix-support strategy for a higher amplitude perturbation. This variability of response choice within and between subjects is also consistent with clinical biomechanics and motor control research. Multi-directional perturbations require complex postural control responses. Combinations of strategies are also often used in response to both unidirectional and multidirectional perturbations (Horak & Nashner, 1986). Henry and colleagues (1998) reported multi-directional perturbations also increase the variability of postural synergy groupings during fixed-support reactions. The context of postural performance and resultant response is based on a number of factors including: biomechanical task constraints, movement strategies, the sensory environment, postural orientation, dynamics of control, cognitive resources, experience and practice, and perception of the goal and its context (Horak, 2006). All these factors help determine the type, magnitude, and variation of the support strategy used (Maki & McIlroy, 1997). These prospective influence factors, other than perturbation characteristics, on MIC initiation potentially influence the current understanding of the effects of platform perturbations on offshore workers and efforts to model this behavior. This could make modeling of response choice a far more complex and difficult task that had original been assumed.

Within this current study perception may have had a significant effect on response choice. While amplitude of the motions differed between trials, subjects may have not always perceived the change in amplitude of the motion or consistently identified these changes in amplitude as events in which change-in-support corrective strategies were needed. Likewise other events of lower amplitudes may have been identified as events precipitating change-in-support strategies. Maurer and colleagues (2006) who found that increases in external stimuli (e.g. size of the perturbations) do not necessarily result in concomitant changes in postural response. These authors concluded that a difficulty with stimulus/response measurement and inherent variation in responses within and between persons limits the current understanding and estimation of threshold values (Maurer et al. 2006). While platform motion profiles of differing severity were randomized to limit potential learning and fatigue effects, failure to perceive changes in stimulus magnitude between motion conditions may have influenced the variability in MIC response and resultant observed initiation thresholds.

Knowledge and prior experience may have significantly affected response choice and therefore apparent effects of amplitude on postural response choice. Knowledge and prior knowledge of the perturbation have been shown to have a significant effect on response choice. There is a tradeoff between speed of compensatory reaction and resultant stability during stepping. Based on these factors the reaction that maximizes dynamic stability for the given situation is chosen (Maki et al., 2003). Experience and prior knowledge of the perturbation affects type and size of the response choice (Punakallio, 2005; McIlroy & Maki, 1995). Increased exposure and practice reacting to specific perturbations reduces the incidence and size of stepping reactions and increases the anticipatory postural adjustments (APAs) used during the stepping reaction (McIlroy & Maki, 1995). Multi-directional wave-induced platform perturbations are generally cyclic in nature with the exception of rogue disturbances. For the purpose of this study wave-form profiles were based on linear wave theory and no abnormalities that may take place at sea were added. The potential for learning and anticipation was possible. While trials were randomized in attempts to limit the effects of learning it is plausible that significant learning effects may prevent any effects of amplitude form being identified.

The effects of perturbation magnitude may be more apparent when postural dynamics are taken into consideration. Previous work by Maki and McIlroy (2001) describes postural response as a relationship between the dynamic movement of the CoM and the BoS. Therefore, when examining postural response both these components must be taken into consideration in addition to MIC or MII occurrence. The effect of amplitude of the wave-motion profile may be related to the dynamics of the CoM and BoS. Due to equipment limitations in the current research, CoM and BoS determination were not possible. Future research that involves measurement of the CoM in relation to the BoS while standing in moving environments would allow for the examination of this relationship, and the potential for more precise input parameters into future prediction models.

Previous research examining the postural responses when exposed to multi-directional perturbations have found changes in neuromuscular response patterns when compared to singular degree of freedom perturbations (Carpenter and Allum, 1999; Henry et al., 1998). Examination of the interaction effects between degrees of freedom of the platform motions at the time of MIC initiation were found to have no significant effect on response choice. This may have been a result of the large pitch and roll amplitudes within the motion profile and the required scaling of the linear displacements in order to fit within the mechanical limits of the motion bed. While these profiles have proven to be valid, the limited magnitudes of motions may have minimized the size and therefore resultant effects of other degrees of freedom. Future work should further examine these interactions between degrees of freedom at time of response in situations that can provide realistic linear displacements.

5.6 CONCLUSIONS

This study has led to the following conclusions:

1. Empirical examination of the effects of changes in platform wave-form amplitude and postural response reveal clear relationships between amplitude of wave-induced platform motions and MIC occurrences when direction of MIC stepping is taken into account.

2. Variability of response, and differing effects of platform kinematics on tasks even after grouping by direction suggests that other factors, including task, in conjunction with platform motion amplitude affect response choice.

3. This information further informs industry of the effects that platform motions have on worker postural stability. Understanding the nature of the perturbation amplitude/MIC relationship, helps determine when workers will be more unstable and at risk for injury and decreased ship operability. This information can then be applied to develop more effective interventions and guidelines to minimize this risk of injury and diminished ship operability.

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CHAPTER 6: THE HABITUATION OF HUMAN POSTURAL RESPONSES TO PLATFORM PERTURBATIONS

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6.1 ABSTRACT

The purpose of this study was to examine the habituation of postural responses to simulated wave-induced ship motions. Twenty-four participants(12 male and 12 female) performed four tasks while being exposed to five motion profiles. Time of motion induced corrections (MIC) occurrence, corresponding platform motion parameters, and total time spent performing MICs were compared between trials. It was found that the number of MIC events and total time spent performing MICs differed significantly between trials, with the first trial for participants having more MIC events and more time spent performing postural corrections. The number of MIC events was reduced and total postural correction times were significantly quicker on the second day of testing. These results suggest that MIC initiation is significantly affected by previous exposure and habituation to comparable platform motions, and could help explain difficulties in previous attempts to predict MIC occurrences purely upon platform motion characteristics.

6.2 INTRODUCTION

Platform motions affect human performance while working in offshore environments (Wertheim, 1998). From a biomechanical perspective these unpredictable and continually changing multi-directional perturbations require complex postural control responses to maintain balance. These platform-related threats to postural stability are problematic for the worker from both an injury and a ship habitability perspective. Previous research has found that the effects of platform motions are related to the wave motion characteristics and the task being performed (Kingma et al., 2003; Matthews et al., 2007; Holmes et al., 2008; Faber et al., 2008; Duncan et al; 2007; Duncan et al., 2010; Duncan et al. 2012).

The naval engineering community has further identified events that have been shown to pose a significant threat to ship habitability. These events, known as motion induced interruptions (MIIs), are incidents where the acceleration due to ship motions become sufficiently large to cause a person to slide or lose balance unless they temporarily abandon their allotted task to make a postural adjustment in order to remain upright (Crossland & Rich, 1998). Applebee (1980), Graham (1989), and Wedge and Langlois (2003) have attempted to predict and model postural response choice and MII occurrence based purely upon platform kinematics. Results from these studies have found that while a relationship between platform motion characteristics and MII occurrence does exist, large amounts of between and within subject variability prevent strong correlations between platform kinematic and stepping response from being established (Langlois et al., 2009). Therefore, magnitude of the motion perturbation cannot be used as the sole predictor of response choice. Research suggests that postural performance is based on a number of factors including: biomechanical task constraints, movement strategies, the sensory environment, postural orientation, dynamics of control, cognitive resources, experience and practice, and perception of the goal and its context to determine the type, magnitude, and variation of the support strategy used (Maki & McIlroy, 1997; Horak, 2006). These responses which may occur well before physics-based stability limits have been reached, as an alternative to fixed-support strategies have been called motion induced corrections. This complex nature of the response to platform motions makes modeling MIIs or MICs a far more difficult task than previously believed.

Knowledge and prior knowledge of the perturbation have been shown to have a significant effect on response choice, by reducing incidence of stepping, decreasing the number of steps, and increasing the anticipatory postural adjustment involved with the stepping reaction (Punakallio, 2005; McIlroy & Maki, 1995). Therefore, learning may significantly affect the reliability of using kinematic-based stepping occurrence prediction models. Previous studies in offshore environments have found that habituation to moving environments with respect to motion sickness occurrence does exist; however, to the authors' knowledge, no studies have examined the effect of learning or habituation on postural stability and postural response. The purpose of this research was to examine whether previous exposure to platform motions might affect the postural response during standing and performance of manual materials handling tasks.

6.3 METHODOLOGY

6.3.1 Participants

Twelve males and twelve females (age: 28.32 ± 5.78 years; stature: 173.35 cm ± 7.16 cm; mass 74.48kg ± 13.32 kg) with limited experience working in moving environments, without a history of susceptibility to motion sickness and free of any known musculoskeletal injury were recruited from a university student population to participate in this study. Participants were exposed to five different motion conditions while performing two stationary standing tasks and two manual materials handling tasks on a six degrees of freedom motion platform. Prior to commencing the study, all participants were presented with documentation outlining the study and were given the opportunity to ask questions of the researchers before signing the consent form. This study was approved by the Human Investigations Committee of Memorial University.

6.3.2 Procedures

Two stationary standing tasks (Parallel and Tandem) and two manual materials handling tasks (Holding and Sagittal Lifting) were performed in five motion conditions. The two stationary standing stances were representative of stances commonly used in response to wave induced platform perturbations, while the two manual materials handling tasks were representative of tasks typically performed. During all trials subjects were asked to move their feet as needed in order to maintain balance. Each condition was five minutes in duration with a period of 5-10 minutes rest in between each condition. All platform motions were performed four times over two separate, two and a half hour sessions.

During each session two of the four tasks were performed in all five platform motion conditions for a total of 10 motion trials in each session. All participants had a minimum of 2 days and a maximum of 7 days between sessions. Task order was randomized.

During the parallel stance task the participant stood with feet shoulder-width apart in a parallel orientation. While in the in-step stance, the participant stood with feet shoulder width apart and the right foot placed anterior of midline and the left posterior of midline. During the stationary holding task the participant was asked to hold a 10kg load in a "dead lift" posture with feet shoulder width apart, arms straight and the load as close to the body as possible. During the lifting/lowering task the participant lifted and lowered a 10kg load directly to and from a shelf 72cm high and 60cm in front of them. Lifts and lowers were performed at a rate of 3 lifts/minute and 3 lowers/minutes. Lifts and lowers were performed consecutively resulting in a task rate of six manipulations/minute and performed using any type of sagittal (freestyle) lifting technique. To ensure participants remained in the same position throughout the task they were asked to keep (or reposition) their toes on a line measured 60cm from the shelf prior to the start of each load manipulation. To aid in accurate box placement during each lift and lower, origin and destination targets were clearly marked on the floor and surface of the shelf. Standardized foot positions were also marked on the floor to aide in repositioning after performing an MIC.

All tasks were performed on a Moog 6DOF2000E electric motion platform *(Appendix A)*. Motion profiles varied in severity. Magnitudes were applied through a range large enough that a MIC would possibly occur, but not so large that subjects would have to continuously alter their base of support (BoS) in order to maintain postural stability. Motion profiles were derived from deck motions collected on a research fishing vessel using a complex linear equation theory *(Appendix B)* (Lloyd, 1993). Amplitudes in the pitch and roll directions were increased by factors of 1.75, 1.875, 2.0, 2.125 and 2.25 relative to the original motion profile to define the five distinct motion conditions. A canopy placed on the motion platform minimized the effects of visual cues (i.e. earth-fixed reference) which could influence a subject's response to a motion perturbation. Participants stood facing the bow of the simulator while performing all tasks in all motion conditions. Task and motion order was randomized between participants.

6.3.3 Data and Statistical Analysis

All motion trials were videotaped and time of MIC initiation was later determined from these video records. An MIC was considered to be any instance when the subject stepped from their original position or grabbed the guard rail during the trial. In order for a stepping or grabbing movement to be considered a new MIC there must have been a minimum of one second between it and the last stepping or grabbing movement. For the purpose of this study, during the lifting/lowering task only MICs that occurred during the act of lifting or lowering (i.e. load manipulation) were recorded.

Amount of time spent performing change-in-support postural corrections during each trial was calculated and compared between trials and days. Time spent performing an MIC was considered to be from the MIC stepping initiation until participants returned and maintained their standardized stance for at least one second. Platform velocities and accelerations in each of the five degrees of freedom at the initiation of MIC events were calculated. Using an 1x20 analysis of variance (ANOVA), with post hoc Tukey pairwise comparisons, these parameters were compared between trials and days to determine if the motions required to evoke MICs significantly differed between trials. All statistical analyses were performed in SPSS for Windows (Release 16.0.0, SPSS Inc.).

6.4 RESULTS

Mean time spent performing MIC related postural corrections and platform kinematics at the time of MIC initiation were calculated for each subject/trial *(Figure 6.1)*. Significant differences in time spent performing MICs between the first trial and all other trials were found (p=0.001). .While MIC occurrence appeared to decrease in all cases on the second day, statistically significant differences between trials of different days were only found between the first trial of the first day and all trials of the second day. No significant differences in time spent performing MICs were found between any of the other trials. Platform kinematics at the time of MIC initiation were also compared. No significant differences in MIC initiation kinematics were found *($p \geq 0.05$)*.

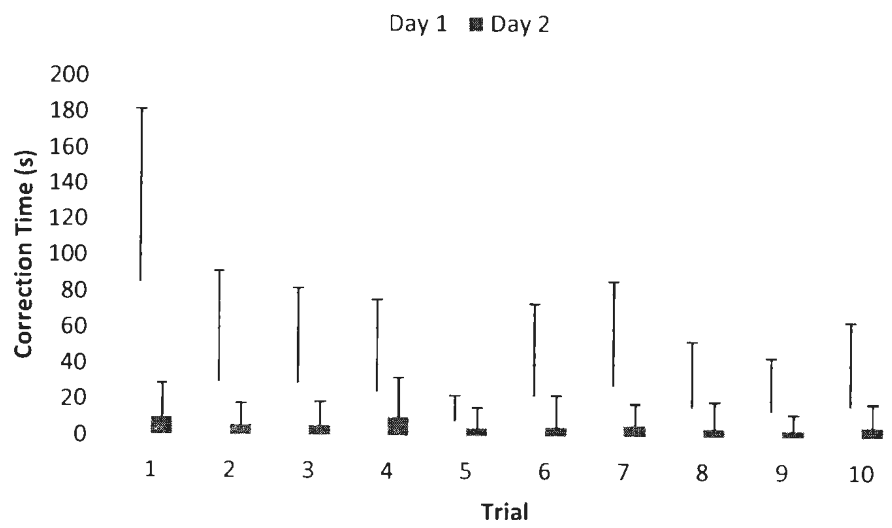

Figure 6.1: Average time spent performing MICs grouped by trial and day they were performed

6.5 DISCUSSION

Previous research that has examined habituation in offshore moving environments from a physiological and motion sickness perspective has suggested that it may take upwards of 48 hours to properly habituate to steady state unidirectional motion (O'Hanlon & McAuley, 1974). Results of this current research suggest that habituation from a postural stability and balance perspective may occur at a much different rate. Greatest differences in MIC occurrence were seen between the first and second trials despite these trials being of different motion states, suggesting that the human body adapts quickly when exposed to the continuous perturbation. Further decreases in MICs were seen between the first and second days of motion trials, despite having a minimum of 48 hours between the trials, suggesting learning effects are still present even after prolonged removal from the moving environment. Additionally, once removed from the moving environment, further adaptations and development of more efficient response strategies in case of future exposures may be possible.

Work that has examined adaptations in postural response have used data collection techniques including surface electromyography and measurement examination of movement of the centre of mass (CoM) with respect to the base of support to gain a greater understanding of the nature of the postural adaptations that occur when exposed to multiple perturbations that are similar in nature (McIlroy & Maki, 1995). Using these techniques it has been found that with experience, movement of the CoM decreases and an anticipatory postural adjustment prior to perturbation onset becomes present. Due to equipment limitations, recording of these experimental measures was not possible for this study. Future work that does examine these factors would help give a greater understanding of the effects of learning and habituation on postural response. It can be hypothesized that, like these previous studies, similar changes in CoM movement with increased exposure would be present; however, the continuous nature of wave-like platform perturbations, that require continuous postural adaptations, may cause differences in neuromuscular activation patterns, particularly in relation to the presence of an anticipatory postural adjustment, when compared to those seen in previous single perturbation studies.

The complexity of the human response choice to postural disturbances has been documented (Horak, 2006; Maurer et al., 2006; Maki et al. 2003). While several researchers have attempted to understand the relationship between perturbation characteristics and MII and MIC occurrence, it has become clear that responses to multidirectional continuous wave motion perturbations are not purely physics based (Langlois et al., 2009). Although magnitude and other characteristics play a significant role in response choice, other factors must be considered. Research must attempt to understand the postural mechanism used to maintain balance in moving environments by identifying these factors and examining their relationship to response choice.

Results of this research suggest that learning may play a role in response choice. Time spent performing MIC corrective strategies were significantly greater during the first trial of the first day of the experimental trials (see *Figure 6.1*). Occurrence and time spent performing MIC type corrective strategies were also statistically significantly greater on the first day across all trials when compared to the second day of trials. These results suggest that learning and habituation to the moving environment significantly affects response choice and resultant MIC occurrence. These findings are consistent with those of Maki and McIlroy (1995) who found that when perturbations are repeated individuals will step less frequently and decrease the number of steps required to maintain balance; however these differences may not be related to the kinematics of platform perturbations. The results of this study suggest that there may be an economy of movement effect present during response choice. When first exposed to the motion, the perturbation is novel and therefore the individual is unaware of the optimal response strategy to use to minimize expenditure and the potential for being more susceptible to destabilizing perturbations in another direction. Therefore, the individual chooses the most robust change-in-support strategy that optimizes the size and shape of the base of support to protect against the current perturbation. As participants are exposed to more perturbations their familiarity with the perturbation increases and with it their ability to develop response strategies that fulfill the aforementioned goals as well as minimizing the biomechanical, physiological, and neuromuscular demands of the response.

It has been hypothesized that continued exposure to the motion would result in decreased incidence of MICs and greater platform kinematics magnitudes required to induce an MIC. While number and length of occurrences significantly decreased between the first and all subsequent trials, there were no differences between corresponding platform kinematics at the time of MIC initiation. This is likely a result of the large amounts of between and within subject variability that existed within the data. These results are consistent with previous findings by McIlroy and Maki (1995) that noted that large amounts of between subject variability existed in adaptive changes to repeated exposure to perturbations. This variability in response s may also be influenced by factors other than learning, including biomechanical task constraints, movement strategies, the sensory environment, postural orientation, dynamics of control, and cognitive resources. Additionally, learning and resultant habituation may take place at different rates between subjects and affect the influence of magnitude on postural response.

Continuous multidirectional perturbations, like those in offshore environments, provide a unique and challenging environment for humans to adapt to in order to successfully maintain balance. While singular, finite perturbations in non-moving environments have been examined for individual and multidirectional perturbations, to the authors' knowledge learning and resultant adaptive changes in postural response in continuous perturbations in moving environments have not been previously examined. McIlroy and Maki (1995) found that responses to the first trial of perturbations were significantly different than subsequent trials; however the characteristics of perturbations did not differ between trials. For each perturbation participants were exposed to the same discrete translational perturbation 600ms in length. In this current research while the first trial of was five minutes of continuous multidirectional perturbations. These current motions were based upon complex sinusoidal wave patterns that differed in magnitude and frequency in the five degrees of freedom, producing a natural feeling wave motion that was somewhat cyclic in nature, while not repeating at any point throughout the trials. Throughout the course of the first trial in this current research study, participants were exposed to many somewhat similar perturbations during which they were continually adapting and developing more optimal postural response strategies. Therefore, the trials in this research study may not be equivalent to those in previous postural stability research. However, examination of time of occurrence of the MICs within the first trial may help determine the extent of adaption within the trial. Since perturbations within the trials are relatively uniform it would be expected that MIC occurrence would be greatest at the beginning of the trial.

It is important to note that while this study does examine the learning and adaptive changes that occur after repeated exposures to similar continuous multi-directional wave-like platform perturbations, it is not a true learning study. In a traditional learning study participants are exposed to the same perturbation multiple times and differences in responses are measured using a repeated measures analysis. This did not occur in this current research study. Participants were exposed to a variety of similar platform perturbations that differed in the amplitudes of the pitch and roll components while performing different tasks and were randomized between subjects. In offshore work environments subjects are exposed to frequently changing perturbations while performing a variety of unique tasks. Despite the limitations of this study, the results of this research are of merit by increasing the current understanding of postural adaptations in moving environments.

From a modelling perspective, the results of this current research further reiterate the need to develop multi-faceted prediction models that incorporate factors other than platform perturbation characteristics. Despite being exposed to similar motions, subjects responded significantly differently initially to perturbations than they did with repeat exposures. While further research is needed to examine the full extent of potential postural adaptations it is clear that these between trial differences and resultant adaptations in postural response could significantly affect the reliability of prediction modelling attempts.

6.6 CONCLUSIONS

When exposed to multiple trials of wave-like multidirectional perturbations, the number of MIC occurrences and amount of time spent performing MIC-related corrective strategies decreased between trials suggesting that learning and habituation may have a significant effect on response choice. These effects appear to be the greatest shortly after exposure to the continuous perturbation, with additional adaptations occurring with further exposures. It is concluded that learning that affects postural response does occur during continued exposure to continuous multi-directional perturbations. Future research should attempt to examine the nature and of this habituation-related response to determine the extent of its effects on postural response.

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CHAPTER 7: DIFFERENCES IN MOTION INDUCED CORRECTION OCCURRENCES BETWEEN STANDING AND MANUAL MATERIALS HANDLING ACTIVITIES

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7.1 ABSTRACT

The purpose of this research study was to examine the differences in motion induced correction (MIC) occurrences when performing standing and manual materials handling tasks (MMH). Twelve male and twelve female participants, with limited experience in motion environments performed two standing and two MMH tasks while being exposed to five different simulated motion conditions. Each task was videotaped and the motion platform kinematics at the time of MIC initiations were calculated and compared using analysis of variance (ANOVA). Results revealed significant differences in pitch and roll velocities between tandem and parallel standing and significant differences in pitch and roll accelerations between both standing tasks and MMH tasks ($p<0.05$). These results suggest that there are quantifiable task related differences in the platform kinematics at MIC initiation. When attempting to model MIC events, for prediction purposes, task characteristics and their effects on MIC must be considered.

7.2 INTRODUCTION

The unpredictable and multidirectional natural forces occurring offshore pose a unique threat to offshore workers. Resultant vessel motions from wave-induced multidirectional perturbations have adverse effects on the human body that can directly affect many aspects of performance. The effects of working in moving environments have been well documents (Wertheim, 1998). Biomechanically these effects are related to the postural adaptations required to maintain balance (Torner et al,, 1994; Kingma et al. 2003; Duncan et al., 2007; Faber et al.,2008; Holmes et al., 2008). In addition to reacting to these postural disturbances, offshore workers must also consider those caused by their occupation-related tasks. Manual material handing (MMH) and stationary standing tasks differ significantly both from a biomechanical and neuromuscular perspective. MMH tasks cause a balance disturbing shift in CoM that must be countered with postural adaptations to prevent instability or falling (Johansson et al., 1991).

Postural adaptations required to maintain balance in continuous moving environments also affect task operability and worker performance. The naval engineering community has identified particular events, called motion induced interruptions (MII) that pose the greatest challenges to postural stability and ship operability. These events include stumbling, sliding and in extreme cases lift-off (Stevens & Parsons, 2002; Baitis et al., 1995; Crossland & Rich, 2000). Physics based modeling approaches have been used to predict MII occurrences typically during stationary standing. However, the same modeling assumptions and parameters used for standing are not valid in all situations and any prediction models must be task dependent. Thus, current models may have limited applications in environments where workers must perform tasks other than standing.

Previous biomechanics studies on moving environments have found that the effects of moving environments on postural response and resultant joint kinematics may potentially differ between tasks (Matthews et al., 2007; Holmes et al., 2008; Duncan et al., 2007; Duncan et al. 2011; Duncan et al.,2012). Although these studies examined MII differences between moving, non-moving environments, no direct comparisons between tasks were made. The extent to which MII occurrence is task dependent is not well understood. Crossland and colleagues (2007) examined MII occurrence in offshore environments, however wave motion characteristics differed between tasks and participants. To further our understanding of the complex postural responses that are required to maintain balance while working in moving environments and aid in the development of more reliable MII models that are applicable across a wide variety of scenarios it first must be determined if the task performed affects MII initiation when exposed to similar wave motions. Therefore, the purpose of this research study was to examine the differences in motion induced correction occurrence between performing standing and MMH tasks.

7.3 METHODOLOGY

7.3.1 Participants

Twelve male and twelve female participants, with limited experience in motion environments and not susceptible to motion sickness were recruited from a university population. Participants performed two standing and two MMH tasks while being exposed to five different simulated motion conditions. The tasks performed were: 1) standing in a parallel stance, 2) standing in a tandem stance, 3) a stationary holding task and 4) a sagittal lifting/lowering task.

7.3.2 Procedures

One standing task required the participant to stand with their feet shoulder width apart in parallel stance and the other standing task required the participant to stand with their feet in a tandem orientation. While performing the stationary holding task, the participant was asked to hold a 10kg load in a "dead lift" posture with feet shoulder width apart, elbows fully extended straight and the load held as close to the individual as possible. During the lifting/lowering task, the participant lifted and lowered the same 10kg load directly to and from a shelf 72cm high and 60cm in front of them. Lifts and lowers were performed at a rate of 3 lifts/minute and 3 lowers/minutes, resulting in six manipulations per minute. This task was performed using a two-handed freestyle lifting technique. An audio cue was used to indicate to participants when to commence lifting or lowering. To ensure the participant remained in the same position throughout the task, visual reference points indicating where to stand were marked on the floor of the motion platform so participants could return to the standardized position after initiating a MIC. To aid in accurate box placement during the manipulations, an origin and destination for the manipulation were clearly marked on the floor and surface of the shelf. While performing activities the participant was told to move their feet naturally whenever they felt it was necessary to maintain balance. During all motion conditions participants faced the bow of the motion platform while performing the tasks.

All motion conditions were collected on a Moog 6DOF2000E electric motion platform (Moog Inc. East Aurora, New York). Each motion condition was five minutes in duration with a period of 5-10 minutes rest in between each trial. Motion profiles used in this research were derived from these wave induced ship motions using linear equation theory (Lloyd, 1993). The motion bed kinematics were based upon data collected during previous research that examined deck motions of various size fishing vessels. Linear equations, where "*t*" represents time in seconds, of the motion profiles used are detailed below *(Appendix B)*. Motion conditions varied in amplitude of the pitch and roll directions. Amplitudes in the pitch and roll directions were increased by a factor of 1.75 (Condition 1), 1.875 (Condition 2), 2.0 (Condition 3), 2.125 (Condition 4) and 2.25 (Condition 5). Due to lack of influence on platform perturbations characteristics in offshore vessel moving environments, yaw motions were not included in the motion profile. A canopy was installed over the motion platform preventing the participants from having any earth related references to help maintain balance.

7.3.3 Data and Statistical Analysis

A MIC was considered to be any instance when the participant stepped from their original position or grabbed the guard rail during the trial. Any stepping motion performed within one second of another was considered to be part of the previous MIC. All trials were videotaped at a rate of 60Hz and the time of MIC initiation was derived from this data stream. Platform motion and video was synchronized by audio and visual cues. Motion platform kinematic characteristics (i.e. angular velocities and accelerations) were later derived from the linear wave equations using these video records. Platform velocities and accelerations for the five degrees of freedom at the time of initiation for each MIC event were calculated from the linear wave equations by substituting time of initiation for each MIC for "t". To determine if the platform motion characteristics at the time of MIC initiation varied significantly due to the postural differences between tasks a 1x4 analysis of variance test (ANOVA) with post hoc Tukey pairwise comparisons were employed ($p<0.05$). All statistical analyses were performed in SPSS for Windows (Release 16.0.0, SPSS Inc.).

7.4 RESULTS

Results of the statistical analysis revealed significant differences in platform motion kinetics in the pitch and roll directions between standing and MMH tasks at the time of MIC event initiation. During forwards stepping events pitch and roll velocities at time of MIC initiation between parallel and tandem standing differed significantly *(Table 7.1)*. Roll accelerations at the time of forwards stepping MIC initiations differed significantly between both standing tasks and lifting, while pitch accelerations during both standing tasks differed significantly from those experienced at the initiation of MIC events during the holding task. Roll velocity during parallel standing was also significantly greater than tandem standing. Statistically significant differences were not seen between holding and lifting tasks for either pitch and roll velocities and accelerations.

Table 7.1: Mean platform velocities and accelerations at the time of forwards stepping MIC events during standing and MMH tasks.

	Velocity (deg/s)		Acceleration (deg/s^2)	
	Roll	**Pitch**	**Roll**	**Pitch**
Parallel	-5.55	-0.31	5.42	-2.29
	(5.35) $_a$	*(5.40)* $_a$	*(6.10)* $_c$	*(9.22)* $_b$
Tandem	-3.04	2.15	6.11	-2.14
	(5.97)	*(5.10)* $_c$	*(6.98)* $_c$	*(9.18)* $_b$
Hold	-5.04	0.34	5.45	2.02
	(5.11)	*(5.13)*	*(7.27)*	*(10.24)*
Lift	-3.63	-0.71	2.92	-0.40
	(7.11)	*(5.52)*	*(7.62)*	*(9.58)*

Note: "*a*" = significance (p<0.05) from tandem standing; "*b*" = significance from holding (p<0.05); "*c*" = significance from lifting (p<0.05).

Platform kinematics in the pitch and roll directions during the initiation of backwards stepping MIC events also were significantly different between tasks. Pitch and roll velocities and pitch acceleration at the time of MIC initiation differed significantly between parallel and tandem standing. Tandem standing accelerations in both pitch and roll directions also differed significantly from those experienced during the initiation of MIC events during the lifting/lowering task.

Table 7.2: Mean platform velocities and accelerations at the time of backwards stepping MIC events during standing and MMH tasks.

	Velocity (deg/s)		Acceleration (deg/s^2)	
	Roll	**Pitch**	**Roll**	**Pitch**
Parallel	5.47 *(5.42)* $_{ac}$	0.32 *(5.39)* $_{a}$	-5.58 *(6.05)*	-0.24 *(9.61)* $_{a}$
Tandem	3.93 *(6.66)*	-1.90 *(5.03)* $_{b}$	-4.87 *(6.79)* $_{c}$	2.36 *(9.56)* $_{c}$
Hold	4.36 *(5.81)*	-0.15 *(5.47)*	-5.98 *(6.61)*	0.30 *(9.71)*
Lift	3.32 *(6.04)*	-0.50 *(5.64)*	-7.02 *(5.96)*	-0.66 *(9.30)*

Note: "*a*" = significance (p<0.05) from tandem standing; "*b*" = significance from holding(p<0.05); "*c*" = significance from lifting (p<0.05).

7.5 DISCUSSION

Previous research has suggested that the biomechanical effects of continuous wave-induced motion perturbations may be influenced by the task being (Duncan et al. 2007). These differences were hypothesized to be related to the differences in postural adaptations required to maintain balance; however, to the authors' knowledge, no direct quantitative comparisons of the postural responses to support this hypothesis have been made. In the present study there were significant differences between standing and MMH tasks in the occurrences of MIC and the platform kinematics at the time of MIC initiation exist. During both forwards and backwards stepping MIC events platform kinematics in the pitch and roll directions differed significantly between different standing stances and between standing and MMH tasks.

Platform kinematics at the time of MIC initiation did not differ between all tasks. Greatest differences in platform for velocities at the time of MIC initiation were seen between parallel and tandem standing stances. Platform accelerations at the time of MIC initiation differed significantly between standing and MMH tasks, while no significant differences in either platform velocities or accelerations between MMH tasks were present. These results appear to be a result of task related differences in size and shape of the BoS. Changing of the size and shape of the BoS changes the participant's susceptibility to motion in the transverse and sagittal planes. Likewise, changes between standing and MMH may be a result of the anterior shift in CoM that occurs when the load is manipulated. Further research which examines the effects of tasks on the CoM/BoS relationship and resultant MIC initiation is needed.

Despite efforts to standardize experimental parameters and potential factors that may influence response choice, large amounts of between participant variability in the initiation of MIC events existed for all tasks. This existence of variability is consistent with that seen in other postural response studies. Despite being performed in controlled environments that attempt to limit the effects of extraneous factors on response choice, large amounts of within and between participant variability on response existed as in other work (McIlroy & Maki, 1997). This ever present variability is believed to be related to the numerous interacting factors that affect response choice. In turn, this complex interaction between factors greatly affects our ability to accurately model postural response.

The results of this study may be of significance to the development of more accurate MIC models. This study suggests that platform kinematics at the time of MIC initiation significantly differ between tasks. While this study did not examine a wide variety of ship related tasks, it did quantitatively compare the platform kinematics to determine if the platform kinematics that are related to the initiation of MIC events differ significantly between types of tasks that may be frequently performed in offshore environments. Results of this current study further suggest that MIC initiation is task dependent. Therefore, to insure validity models cannot be based upon stationary standing that is applied to all tasks and situation, but instead must be task . These task dependent models should not only be based upon the platform accelerations at the time of MIC initiation but also the dynamics of the CoM with respect to the BoS before and at the time of response initiation.

Furthermore the results of this study support the idea that specific MMH tasks may pose a greater risk to worker safety than others. While the effects, and resultant risks, of MMH tasks on musculoskeletal injury have been well documented, the additional potential extent to the effects of performing these strenuous tasks in moving environments had not been known. To the authors' knowledge this study is the first to examine different MMH tasks while being exposed to the same motion conditions. Results of this study clearly suggest that performance of particular MMH tasks in a moving environment result in further instability compared to a stationary environment that, in turn, may increase risk of falling, decrease task operability, and may increase risk of musculoskeletal injury. Further research is required to determine the extent of the risks from increased instability while performing MMH tasks in moving environments.

From an MII modeling perspective these results clearly suggest that individual tasks must be taken into consideration in order to develop accurate prediction models. It may be possible to develop a model in which the load which is manipulated is considered an external perturbation similarly to the wave-induced platform perturbations. In doing so, input parameters could be developed so that each unique task does not have to be examined individually. Future research should attempt to determine which method is best to incorporate MMH tasks and their resultant effect on model accuracy.

7.6 CONCLUSIONS

This research study has led to the following conclusions:

1. Platform kinematics during MIC initiation differs significantly between standing and MMH tasks. This suggests that some tasks may have a greater effect on postural instability than others.

2. Variability within the dataset suggests that further examination of the task related differences in postural responses, including analysis of the CoM/BoS relationship, is needed to examine the differences CoM movements during at the MIC initiation.

3. Given the task dependent nature of MIC initiation, in order to insure validity MIC prediction models must take into account the task parameters of each individual task being performed when predicting MIC occurrence in an occupational moving environment.

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CHAPTER 8: OVERVIEW AND DISCUSSION

8.1 INTRODUCTION

The purpose of the research program was to examine how humans respond to working in moving environments. This information is necessary so that work at sea can be made as efficient and safe as possible. This work will inform human factors specialists, ship designers and those responsible for managing people who work at sea.

Two experiments were conducted to achieve this purpose. The first experiment provided information examining differences in platform kinematics between MIIs and MICs at the time of event initiation. In previous work an MII has been defined as an interruption, such as a step or a slide, made by the participant as a last resource to maintain balance. The concept of a MIC is introduced in this work as a correction a subject will make before it is absolutely necessary to step. These are events are based upon the concept of a change-in-support mechanism. Participants performed standing tasks that were representative of the demands to evoke MIIs and MICs. The constrained task represents the demands upon the participant consistent with evoking an MII while the unconstrained task was representative of the demands upon the participant consistent with MICs. The results of this first experiment determined that MICs and MIIs were different phenomena caused by different platform kinematics and that people respond to these motions in different manners. Therefore, MIIs and MICs could not be treated as the same events.

The second experiment assessed if platform kinematic could accurately predict MIC occurrences. Participants were asked to move their feet whenever necessary to maintain balance while being exposed to a range of wave-like platform perturbations which varied in magnitude. Results of this study found that when MICs events were examined together, no clear amplitude-MIC response was apparent; however, when direction of stepping was taken into consideration a clear relationship between platform kinematics and MIC occurrence appeared. Nevertheless, large amounts of variability in the timing of MICs and corresponding platform kinematics between and within participants existed. Therefore, subsequent analyses of these data focused on determining if other measurable factors were related to this variability. These analyses examined the effects of exposure time and task on MIC initiation and corresponding platform kinematics at the time of MIC initiation

Data from Experiment 1 were considered in the following chapters:

1. Stepping response during constrained and unconstrained standing in moving environments (Chapter 3).

2. A comparison of platform motion waveforms during constrained and unconstrained standing in moving environments (Chapter 4).

Data from Experiment 2 were considered in the following papers.

1. The relationship between ship deck motions and human motion induced correction initiation (Chapter 5).

2. The habituation of human postural responses to platform perturbations (Chapter 6).
3. Differences in motion induced correction occurrences between standing and manual materials handling activities (Chapter 7).

This dissertation tested the following hypotheses

Hypothesis 1: While being exposed to wave-like platform perturbations the motions that cause MII and MIC are significantly different. This hypothesis was tested in *Experiment 1* and discussed in *Chapter 3* and *Chapter 4*. These chapters concluded that MIIs and MICs are events which differ in occurrence and magnitude of platform perturbations at the time of event initiation. This alternative hypothesis can be accepted.

Hypothesis 2: MIC occurrence while performing standing and MMH tasks can be predicted solely upon platform perturbation characteristics. This hypothesis was tested in *Experiment 2* and reported upon in *Chapter 5*. As concluded in this chapter, when the direction of the MIC is taken into account a relationship between MICs and platform perturbation characteristics appears to exist. However, due to large amounts of variability within the sample the appropriate tests to determine if platform perturbation characteristics could solely predict MICs could not be performed. Therefore, at this time the hypothesis cannot be accepted.

Hypothesis 3: The factors of exposure time and task performance have an influence on MIC initiation. This hypothesis was tested in *Experiment 2* and discussed in *Chapters 6 and 7*. In these chapters it was concluded that exposure time and task performance has a significant influence on MIC initiation. This hypothesis can be accepted.

8.2 IMPACT OF RESEARCH

This work tested current theories in postural response choice promoted by the biomechanical and motor control communities data collected in continuous moving environments. Furthermore, novel analytical approaches were employed to understand better the information collected in the two experiments. This work supports the maritime community in understanding how humans respond to moving environments. The following summarize the findings of this research, with respect to how they pertain to current definitions approach MIIs and human response to moving environments can be made *(Figure 8.1)*.

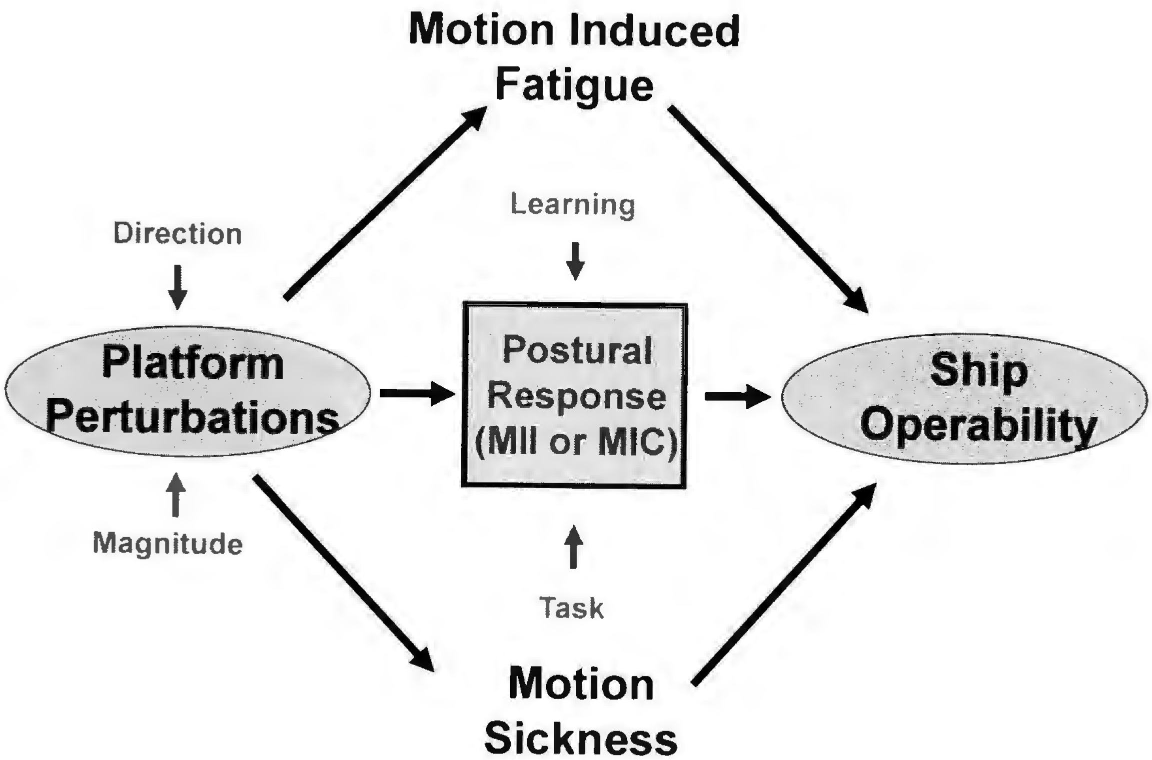

Figure 8.1: Contributions to the Human Performance at Sea Model

Current definitions of MIIs were developed in the early 1980s by Applebee, Baitis, and colleagues, physics-based relationship, which suggested that humans would only step to maintain balance once all methods that do not involve movement of the feet have been exhausted (Applebee et al., 1980; Baitis et al., 1984). Research in the area of postural control has led to theories with regards to change-in-support reaction (Maki and McIlroy, 2003). There was need to determine if these ideas are applicable to MII research and reflect the current understanding of postural responses in moving environments. This was done by examining these definitions *in vivo* through the application of current biomechanical and motor control theories on postural control. The results of this research suggest that change-in-support strategies used in moving environments (i.e. MIIs or

MICs) may not necessarily be a response used as last resort to prevent complete loss of balance, but instead may be used as an alternative to fixed-support strategies in order to maintain a desirable level of stability. These events, therefore, may not inevitably interrupt the performance of the current task and thus decrease habitability or safety. In turn, the current definition of a MII may not be applicable in all maritime occupational situations; thus this research group presents the alternative definition of a MIC to describe change-in-support mechanisms which occur in offshore occupational environments.

8.3 FACTORS INFLUENCING RESPONSE CHOICE

8.3.1 Perturbation Magnitude-MIC Initiation Relationship

When all MICs were examined together, regardless of stepping direction, platform kinematic magnitudes could not be related to a MIC initiation. However, when MICs were grouped and analyzed by direction of stepping, a clear perturbation magnitude-MIC initiation relationship became evident. These results in *Experiment 2* support those of *Experiment 1* and suggest that while magnitude of the platform perturbation plays a role in response choice this relationship is quite variable, with participants frequently performing MICs at lower platform kinematic magnitudes than ones that did not result in MICs in the same trial or other identical trials. This variability is consistent with previous MII studies and suggests that while platform kinematics plays a significant role in MIC initiation other factors may also contribute to response choice and resultant variability in MIC initiation.

8.3.2 Learning and Experience

Large amounts of between and within participant variability in MII and MIC initiations and platform kinematics existed for both experiments. Large amounts of variability are commonly reported in the motor control and biomechanical literature. Much of this variability is believed to be related to other factors that may influence the postural response choice (Maki & McIlroy, 1997). These factors include, but are not limited to learning, fatigue, task, cognitive awareness, and prior experiences (Punakallio, 2005; Horak and Nashner, 1986; McIlroy & Maki, 1995; Hof et al., 2005). Analyses of the of the data from *Experiment 2* looked at the nature of this variability by examining the potential influences of experience time and task MIC initiation and corresponding platform kinematics at the time of MIC initiation.

These analyses found trial differences between time spent performing MICs. This suggests that response may be dependent on exposure to the data collection protocol. Experience may also play a significant role on postural response choice when exposed to continuous multi-directional perturbations. Previous work by McIlroy and Maki (1995) has found that occurrence of change-in-support responses decrease with repeated perturbation exposure. This is believed to be as a result of participants learning more efficient fixed-support strategies. Therefore, MIC occurrence may potentially decrease with learning as more optimal fixed-support strategies that limit possible destabilization, from stepping and resultant susceptibility to perturbations in another plane during this destabilization, become available. In order to understand the true effects of experience time and resultant learning that may arise from it, future research needs to explore further the degree of this response through experimental designs in which participants are repeatedly exposed to the same perturbations. Future work may also wish to consider the effects of exposure duration and frequency and the effects of prolonged occupational exposures to moving environments effect response choice. Previous experience may also affect response choice. For the purpose of this research, attempts were made to control participant experiences to offshore environments which might influence the postural response choice and resultant MIC initiation. To the author's knowledge, there is limited research on the effects of experience on postural response. While this current research suggests that repeated exposure to motion plays a role in response choice, the effects of prolonged exposure from working in these environments remains unknown.

The effects of experience on MIC initiation when exposed to continuous multi-directional perturbations may not be mediated only by time spent in these environments. The literature suggests that unrelated activities such as dancing and yoga affect postural response to perturbations (Hart & Tracy, 2008; Simmons, 2005; Zhang et al., 2008). Previous involvement in these types of activities may significantly affect postural response in moving environments and resultant MIC initiation. as well as the resultant ability to predict these events.

8.3.3 Task

Tasks being performed by the participant while exposed to platform perturbations were also shown to have an effect on MIC initiation with significant differences between tandem stances, parallel stances, and MMH activities. This may be a result of the changes in CoM dynamics through from the manipulation of the external load. Manipulation of the external changes the relative position of the BoS, changing the susceptibility of the participant to perturbations. This may result in either increased or decreased probability of MIC occurrence depending on the positional change of the CoM and the corresponding platform perturbation. Differences between standing stances also suggest that manipulation of the size and shape of the BoS influences susceptibility to perturbations and resultant MICs. When examining the effects of task on MIC initiation the unique characteristics of the task, and corresponding motions must be taken into consideration.

Although not examined in this current research, cognitive demands and fine motor tasks may also affect response choice. Previous research in offshore environments on the cognitive demands and postural response is limited. To the authors' knowledge, no studies have attempted to examine the effects of cognitive demands on postural response. However, results of previous motor control research suggest that cognitive demands on attention may have a greater effect on fixed support strategies than change-in-support strategies (Maki and McIlroy, 2003). In cases where cognitive demands are divided between maintaining balance and performing an additional task, change-in-support strategies may be preferable, and therefore used more often, resulting in increased occurrence of MICs.

8.4 RETHINKING THE MII APPROACH TO PREDICTING SHIP OPERABILITY

This research furthers the current understanding of how human respond to offshore moving environments by suggesting that current postural control literature may apply to the continuous multi-directional perturbations observed in offshore environments. Repeated attempts to develop and validate MII prediction models based solely upon Newtonian mechanics and the idea of a hierarchy of response choices have found that postural response is highly variable and likely cannot be based purely on perturbation characteristics. Results of this research give greater insight into the nature of human response to these environments and the complex challenges associated with predicting postural response through the application of ideas and theories developed from previous biomechanical and motor control related postural stability research.

It was hypothesised that any events involving the movement of the feet to change the size and shape of the BoS were last resort efforts only used after all other fixed-support postural strategies had been exhausted (Applebee et al., 1980; Graham, 1989). Additionally, it was believed that all events which fell under the definition of an MII would affect ship operability (Applebee et al., 1980). While stepping, slipping and lift-off of events be classified as MIIs, all result in some degree of postural instability; the circumstances that produce these events, however, are potentially very different from each other, and therefore these instances cannot be classified as the same event. For the purpose of this research, only change-in-support mechanism events were examined. If these events are not used as a last resort, it is plausible that these events may not have the same effect on task performance and in some cases change-in-support mechanisms such as MIIs or MICs may be more biomechanically and physiologically beneficial to postural control than fixed-support alternatives. Instead of focusing on postural responses (i.e. MIIs or MICs), it may instead be more beneficial to examine the resultant effects of these responses on task execution. Future research should attempt to examine the effects of postural responses on task-related risk of injury to determine and a clear relationship exists between response choice and performance.

8.5 FUTURE DIRECTIONS

8.5.1 CoM/CoP Dynamics

To date, experimental designs which involve three dimensional postural analysis and CoM/BoS evaluation have been limited. This is most likely due to the limitations and challenges of collecting 3D kinematics and kinetic parameters in a fully immersed moving environment in which the participant and equipment are both exposed to the perturbations. While, Faber et al. (2008) had the resources to install the apparatus necessary to collect these data, such an endeavour was not possible for this current doctoral dissertation or during previous studies with this research group. Alternative measures including MII/MIC initiation, thoraco-lumbar kinematics, and individual foot CoP, have been used to gain insight into the effects of moving environments on postural response (Duncan et al., 2007; Holmes et al., 2008; Matthew et al., 2007; Duncan et al., 2010; Duncan et al.,*2012*). Within the postural control literature, however, analysis of CoM dynamics is an integral part of the body of research. Numerous studies examining the effects of perturbations on postural response have focused on the effects of perturbations on CoM dynamics and the relationship between the CoM and BoS (Hof et al.,2005; Pai et al., 2000; Maki and McIlroy et al., 1997). These studies illustrate the need to develop experimental designs that examine CoM dynamics, and the relationship between CoM and BoS, while being exposed to continuous multidirectional perturbations. Through the analysis of these variables it may be possible to gather a greater understanding of relationship platform perturbation characteristics and MIC initiations. This information, in turn, can be used to develop more accurate MIC prediction models.

8.5.2 Neuromuscular Activation & APA Development

Previous neuromuscular research which has examined postural response to instantaneous perturbations has suggested that co-activation of trunk musculature is used to stabilize the spine and maintain stability. With change-in-support reactions, specific neuromuscular recruitment strategies are dependent on the characteristics of the perturbations (McIlroy & Maki, 1999; Aruin et al., 2003). To date, examination of MIIs and postural responses has focused primarily on event initiation and corresponding biomechanical, kinematic, and kinetic effects; however, research examining the neuromuscular responses to wave-induced platform perturbations is limited. Future research should attempt to examine complex neuromuscular effects of continuous multi-directional perturbations on postural response and resultant task operability and injury risk.

Examination of neuromuscular parameters is also necessary to further the current understanding of APAs and change-in-support events. Research suggests that during change-in-support reactions anticipatory postural adjustments are smaller. With change-in-support reactions, specific neuromuscular recruitment strategies are dependent on the characteristics of the perturbations (McIlroy & Maki, 1993; McIlroy & Maki, 1999; Aruin et al., 2003). Learning may also affect the APA involved with the MII or MIC event. APAs are dependent on the magnitude and direction of the expected perturbation (Aruin, 2003). If prior of knowledge of stimulus is limited, then too should be the APA. However, as perturbations are repeated and cyclical in nature, APAs become more pronounced (McIlroy & Maki, 1993). With increased exposure to the perturbation, the human body can develop more efficient APAs and resultant postural responses. The sometimes cyclic and predictable nature of wave-induced platform motion may influence the use and development of APAs. Future research should attempt to examine complex neuromuscular effects of continuous multi-directional perturbations on APA development and MIC initiation as well as resultant task operability and injury risk.

8.5.3 Re-evaluating Human Performance at Sea Models

The results of this research also impact the current understanding of how human performance is affected by wave-induced platform perturbations. Traditional models suggest that platform perturbations independently affect the human body through increasing fatigue, MIIs, and motion induced sickness *(Figure 1.1)*. These effects, in turn, result in performance decrements. Through the application of biomechanical and motor control theories of postural response, and results of this dissertation, additions can be made to this model *(Figure 8.2).*

Biomechanical and neuromuscular control research suggests that motion induced sickness, motion induced fatigue and postural response may be interdependent upon one another. Research by Wilson and colleagues (2006) has suggested muscular fatigue may significantly influence postural response to perturbations. Other research has shown that postural instability is often a precursor to motion sickness (Stoffregen et al. 2000; Bonnet et al., 2006). When examining these factors in moving environments their interdependence with one another must be considered. Further, additional factors that may influence postural response choice including but not limited to experience, learning, task constraints and their resultant effect on CoM dynamics must also be considered (Punakallio, 2005; Horak and Nashner, 1986; McIlroy & Maki, 1995; Hof et al., 2005). While attempts were made during the progression of this dissertation to examine the relationship between multiple factors (motions, learning, task, etc.) and their contribution to MIC occurrence, the statistical power required to develop such a predictive model was not present. Future work should attempt to develop this potential empirically based prediction model.

The resultant effects of moving environments have been shown to be detrimental to human performance. This effect can be further categorized into effects on worker performance and musculoskeletal injury. Effects on worker performance result in decreased task operability and ship operability. Previous biomechanics research has found that moving environments result in increased joint kinematics and mechanical loading of the joints which may, in turn, increase risk of cumulative musculoskeletal injuries (Torner et al., 1994; Kingma et al., 2003; Duncan et al., 2007; Matthews et al., 2007; Holmes et al., 2008; Faber et al., 2008; Duncan et al., 2010; Duncan et al., *2012*). These effects of task operability and potential injury are also interdependent as task operability may be influenced by injuries endured as a result of performance and likewise, performance of task may also influence musculoskeletal injuries.

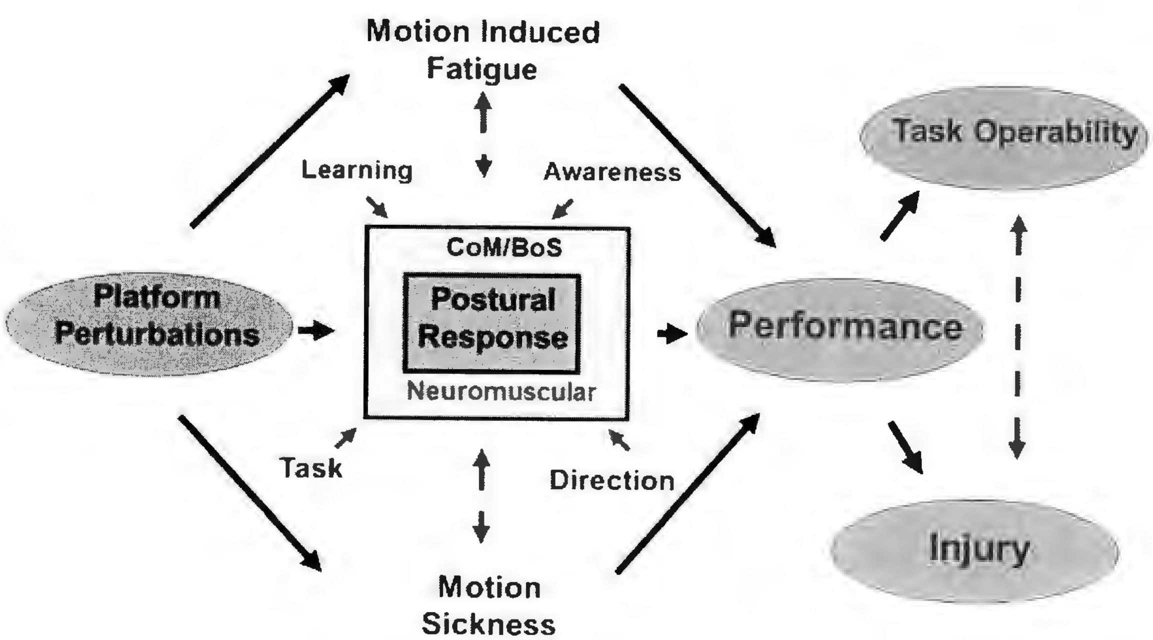

Figure 8.2: Updated Model of Human Performance in Moving Environments

8.6 CONCLUSIONS

The following conclusions are made:

1. MIIs and MICs are distinctly different phenomena which differ in occurrence, duration, and platform kinematics at the time of event initiation. When exposed to continuous multi-directional perturbations, like those offshore, individuals will step whenever necessary to maintain balance. This may occur at platform perturbation magnitudes at which it may be possible to maintain balance without stepping. These events may be well before the theoretical physics-based stability limits have been reached. When examining postural response in offshore occupational environments, MIIs or MICs cannot be characterized as a last resort event, used only once all other strategies have been exhausted.

2. MIC initiation cannot be predicted solely upon platform perturbation kinematics. While platform kinematics at the time of MIC initiation may play a large role in event occurrence, other factors, such as task characteristics and experience, may affect response. These factors must be considered when attempting to develop accurate MII and MIC prediction models.

3. When attempting to examine the effects of moving environments on postural response and resultant task efficiency or ship operability, occurrence of change-in-support strategy type MII or MIC events may not be good predictors. The nature of change-in-support reactions as an alternative to fixed support strategies potentially mean task and ship operability are not significantly affected during all events. Before continuing to use MIIs or MICs as measure of ship operability, further examination of their effect on ship operability is required.

4. From a human factors and user standpoint this research suggests that change-in-support mechanisms, such as MICS, may not necessarily suggest greater postural instability than fixed-support alternatives. When examining these responses in offshore environments the resultant outcome of the MIC should be examined on a case-by-case basis. This examination should focus on the acute and cumulative injury caused by the performance of the event.

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APPENDICES

APPENDIX A: MOTION PLATFORM SPECIFICATIONS

Figure A.1: Motion Bed Schematic

Table A.1: Motion Bed Specifications (Moog Inc.)

Degree of Freedom	Displacement Comb. Motion	Displacement Single DOF	Velocity	Acceleration
Pitch	+25/-23 deg	±22 deg	±30 deg/s	±500 deg/s
Roll	±22 deg	±21 deg	±30 deg/s	±500 deg/s
Yaw	±23 deg	±22 deg	±40 deg/s	±400 deg/s
Heave	±0.18m (±7.0 in)	±0.18m (±7.0 in)	±0.30m/s (±11.8 in/s)	+0.5 g
Surge	±0.27m (±11.1 in)	±0.25m (±10.2/-9.5 in)	±0.50m/s (±19.7 in/s)	±0.6 g
Sway	±0.26m (±11.7 in)	±0.25m (±10.2 in)	±0.50m/s (±19.7 in/s)	±0.6 g

APPENDIX B: MOTION PROFILE EQUATIONS

APPENDIX B: Platform Motion Wave Equations and Characteristics

$$Roll = 0.8(6\sin(1.050t) + 1.25\sin(0.11t + 0.5)) \quad (1.1)$$

$$Pitch = 0.8(2.5\sin(1.76t + 0.5) + \sin(t) - 1.5) \quad (1.2)$$

$$Heave = 0.1(5\sin(1.595t + 2) + 15\sin(1.21t)) \quad (1.3)$$

$$Surge = 0.1(7.8\sin(0.649t + 4.8) + 7.8\sin(0.825t + 3.8) + 0.5) \quad (1.4)$$

$$Sway = 0.1(18\sin(0.583t + 5) + 9\sin(1.122t + 5.4) - 0.25) \quad (1.5)$$

APPENDIX C: MOTION PROFILE CHARACTERISTICS

Table C.1: Experiment 1Platform Displacement Characteristics

Degree of Freedom	Baseline Amplitude RMS	Baseline Amplitude Max.	Baseline Amplitude Min.	Increased Amplitude RMS	Increased Amplitude Max.	Increased Amplitude Min
Sway (m)	0.02	0.04	-0.04	0.02	0.04	-0.04
Surge (m)	0.04	0.07	-0.07	0.04	0.07	-0.07
Heave (m)	0.01	0.02	-0.02	0.01	0.02	-0.02
Pitch (deg)	3.47	5.80	-5.80	8.67	14.49	-14.50
Roll (deg)	1.94	1.60	-4.00	3.98	5.80	-8.20
Yaw (deg)	0.00	0.00	0.00	0.00	0.00	0.00

Table C.2: Experiment 1 Platform Velocity Characteristics

Degree of Freedom	Baseline Amplitude RMS	Baseline Amplitude Max.	Baseline Amplitude Min.	Increased Amplitude RMS	Increased Amplitude Max.	Increased Amplitude Min.
Sway (m/s)	0.01	0.03	-0.03	0.02	0.03	-0.03
Surge (m/s)	0.03	0.05	-0.05	0.03	0.05	-0.05
Heave (m/s)	0.02	0.03	-0.03	0.02	0.03	-0.03
Pitch (deg/s)	3.56	5.15	-5.15	9.32	13.47	-13.46
Roll (deg/s)	2.55	4.32	-4.32	6.51	9.50	-9.50
Yaw (deg/s)	0.00	0.00	0.00	0.00	0.00	0.00

Table C.3: Experiment 1 Platform Acceleration Characteristics

Degree of Freedom	Baseline Amplitude RMS	Baseline Amplitude Max.	Baseline Amplitude Min.	Increased Amplitude RMS	Increased Amplitude Max.	Increased Amplitude 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 C.4: Experiment 2 Platform Displacement Characteristics

Degree of	Condition 1			Condition 2			Condition 3			Condition 4			Condition 5		
Freedom	RMS	Max.	Min.	RMS	Max.	Min.	RMS	Max.	Min.	RMS	Max.	Min.	RMS	Max.	Min.
Sway (m)	0.02	0.04	-0.04	0.02	0.04	-0.04	0.02	0.04	-0.04	0.02	0.04	-0.04	0.02	0.04	-0.04
Surge (m)	0.04	0.07	-0.07	0.04	0.07	-0.07	0.04	0.07	-0.07	0.04	0.07	-0.07	0.04	0.07	-0.07
Heave (m)	0.02	0.03	-0.03	0.02	0.03	-0.03	0.02	0.03	-0.03	0.02	0.03	-0.03	0.02	0.03	-0.03
Pitch (deg)	5.79	9.75	-9.75	6.50	10.88	-10.88	6.93	11.60	-11.60	7.36	12.32	-12.32	7.80	13.05	-13.05
Roll (deg)	2.48	3.30	-3.70	2.65	3.63	-3.87	2.83	3.95	-4.05	3.01	4.27	-4.23	3.18	4.59	-4.41
Yaw (deg)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table C.5: Experiment 2 Platform Velocity Characteristics

Degree of	Condition 1			Condition 2			Condition 3			Condition 4			Condition 5		
Freedom	RMS	Max.	Min.	RMS	Max.	Min.	RMS	Max.	Min.	RMS	Max.	Min.	RMS	Max.	Min.
Sway (m/s)	0.02	0.03	-0.03	0.02	0.03	-0.03	0.02	0.03	-0.03	0.02	0.03	-0.03	0.02	0.03	-0.03
Surge (m/s)	0.03	0.05	-0.05	0.03	0.05	-0.05	0.03	0.05	-0.05	0.03	0.05	-0.05	0.03	0.05	-0.05
Heave (m/s)	0.03	0.05	-0.05	0.03	0.05	-0.05	0.03	0.05	-0.05	0.03	0.05	-0.05	0.03	0.05	-0.05
Pitch (deg/s)	4.99	7.73	-7.72	5.61	8.66	-8.65	5.99	9.23	-9.23	6.36	9.81	-9.80	6.74	10.39	-10.38
Roll (deg/s)	3.48	4.93	-4.93	3.73	5.28	-5.28	3.98	5.63	-5.63	4.23	5.98	-5.98	4.48	6.34	-6.34
Yaw (deg/s)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table C.6: Experiment 3 Platform Acceleration Characteristics

Degree of	Condition 1			Condition 2			Condition 3			Condition 4			Condition 5		
Freedom	RMS	Max.	Min.	RMS	Max.	Min.	RMS	Max.	Min.	RMS	Max.	Min.	RMS	Max.	Min.
Sway (g)	0.12	0.24	-0.24	0.12	0.24	-0.24	0.12	0.24	-0.24	0.12	0.24	-0.24	0.12	0.24	-0.24
Surge (g)	0.25	0.48	-0.48	0.25	0.48	-0.48	0.25	0.48	-0.48	0.25	0.48	-0.48	0.25	0.48	-0.48
Heave (g)	0.26	0.47	0.00	0.26	0.47	0.00	0.26	0.47	0.00	0.26	0.47	0.00	0.26	0.47	0.00
Pitch (deg/s/s)	4.37	6.45	-6.45	4.92	7.25	-7.25	5.25	7.73	-7.73	5.57	8.21	-8.21	5.90	8.70	-8.70
Roll (deg/s/s)	4.91	6.94	-6.94	5.26	7.43	-7.43	5.61	7.93	-7.93	5.96	8.43	-8.43	6.31	8.92	-8.92
Yaw (deg/s/s)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0