STEPPING RESPONSE DURING CONSTRAINED AND UNCONSTRAINED STANDING IN MOVING ENVIRONMENTS

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SUMMARY

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 (10 male and 10 female), with limited experience recreating or working in motion-rich 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 all three 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. As such, stepping should not be considered as a last resource when all fixed-support options have been exhausted. This should be taken into consideration to ensure ecological validity when developing models to predict stepping occurrence.

1. 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 and colleagues [1] 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 negative changes in biomechanical variables such as trunk kinetics and kinematics when working in moving environments [2, 3, 4,5,6,7]. 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 (MII), are incidents where the ship motions increase to the point at which they 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 [8].

The concept of an 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 [9,10,11]. This was later expanded upon by Baitis and colleagues to include three distinct types of events [8,12,13]. 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 [12,13].

Modelling techniques to predict the occurrence of MIIs have been published [11,14]. 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 a 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 the overall ecological validity of this approach [15].

Current thinking regarding MIIs assumes all corrective foot actions (ie., moving of the feet) that a person makes are adaptations to maintain postural stability after all efforts to maintain a fixed-foot support strategy 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 (BoS) [16, 17].

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 (ie., 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 [15,18,19]. These strategies of continuous operator foot adjustments have been termed, in this work, as motion induced corrections (MIC) and 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 contradicts 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 between MIIs and MICs 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.

2. METHODS

2.1 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 limited 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.

2.2 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 an MII. An unconstrained task allowed the participant to freely move their feet whenever it was felt that loss of balance might occur. This outcome response was considered to be a 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. All motion conditions were performed on a Moog 6DOF2000E electric motion platform. Motion conditions varied in amplitude and were derived from captured wave induced ship motions using linear wave theory [19] *(Equations 1-5)*. Linear waveforms were applied concurrently to one another. 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 magnitude of all six degrees of freedom. This process allows for systematic changes to each degree of freedom of the motion. For the increased amplitude condition, the amplitude of the pitch and roll directions was increased by a factor of 2.25 *(Tables 1-3)*.

$$Roll = 0.8(6\sin(1.050t) + 1.25\sin(0.11t + 0.5)) \quad (1)$$

$$Pitch = 0.8(2.5\sin(1.76t + 0.5) + \sin(t) - 1.5) \quad (2)$$

$$Heave = 0.1(5\sin(1.595t + 2) + 15\sin(1.21t)) \quad (3)$$

$$Surge = 0.1(7.8\sin(0.649t + 4.8) + 7.8\sin(0.825t + 3.8) + 0.5) \quad (4)$$

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

Table 1: Motion profile displacement characteristics

Degree of Freedom	Baseline Amplitude			Increased Amplitude		
	RMS	Max	Min	RMS	Max	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 2: Motion profile velocity characteristics

Degree of Freedom	Baseline Amplitude			Increased Amplitude		
	RMS	Max	Min	RMS	Max	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 3: Motion profile acceleration characteristics

Degree of Freedom	Baseline Amplitude			Increased Amplitude		
	RMS	Max	Min	RMS	Max	Min
Sway (g)	0.11	0.22	-0.22	0.12	0.24	-0.24
Surge (g)	0.23	0.44	-0.44	0.25	0.48	-0.48
Heave (g)	0.24	0.43	0.00	0.26	0.47	0.00
Pitch (deg/s/s)	3.74	5.30	-5.30	10.24	14.51	-14.50
Roll (deg/s/s)	4.42	6.99	-6.99	11.97	16.97	-16.97
Yaw (deg/s/s)	0.00	0.00	0.00	0.00	0.00	0.00

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.

2.3 DATA AND STATISTICAL ANALYSIS

All motion trials were videotaped. 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 calculated from the corresponding motion profile equations. Pilot work previous to commencement of this study revealed that platform motions in the pitch and roll directions have the greatest effect on postural response and as such, for the purpose of this research study, only platform kinematics in these degrees of freedom were examined.

Student's *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. RESULTS

3.1 MII VERSUS MIC OCCURRENCE

Occurrence of stepping differed significantly between unconstrained and constrained standing *($p<0.01$) (Figure 1)*. During unconstrained standing subjects stepped more frequently than during constrained standing in all motion conditions. Occurrence of both constrained and unconstrained stepping significantly differed between motion conditions *($p<0.01$)*. Greatest increases, in both constrained and unconstrained stepping, occurred with increasing the amplitude of the pitch and roll waveforms. Large standard deviations identify that during all three motion conditions stepping was highly variable between subjects.

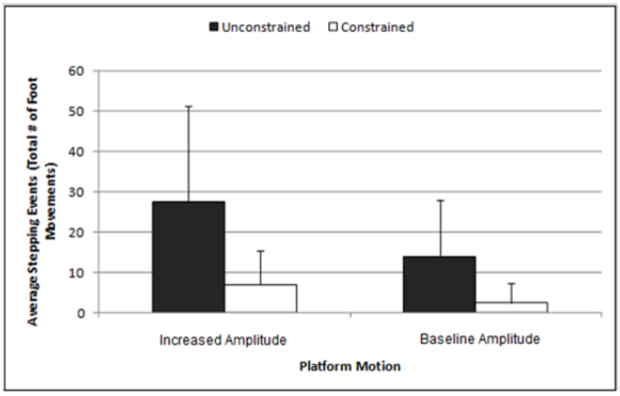

Figure 1: Average subject unconstrained and constrained stepping occurrence (and standard deviations) for each motion condition with standard deviations.

3.2 MEAN PLATFORM VELOCITIES AND ACCELERATIONS

Due to low stepping occurrences during baseline amplitude motion condition, statistical analysis was not possible. Therefore statistical analysis was only performed for the increased amplitude condition. No significant differences ($p > 0.05$) in mean velocities or accelerations between MIIs and MICs were found for forwards or backwards stepping events *(Tables 4 and 5)*.

Table 4: 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 5: 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)*

4. DISCUSSION

The American, British, Canadian, and Dutch (ABCD) model of human performance at sea suggests that wave-induced ship motions have a number of effects on the human body that individually affect human performance. These include motion induced fatigue, motion sickness, and motion induced interruptions [21]. Previous research suggests that the current standards and definitions do not accurately represent the human postural response to wave-induced ship motions. Attempts to validate modelling 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 theory [8,12,15]. Lewis and Griffin [22] further suggest 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 is to assess the occurrences of MICs and MIIs when subjects are exposed to simulated wave-induced ship motions in an attempt 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. This confirmed 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 [17]. 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 between MIIs and MICs were found. These results may be a result of the large between-participant variability which is attributable to the innate variability between participants as well as other factors which may influence response choice. Therefore, no significant differences between groups were found. 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 [22] 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 that 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, and therefore making it difficult to develop critical values for even occurrence. These findings suggest that response choice is most likely situation dependent and experience related and thus supports the idea that response choice is highly related to human cognition and other influences that are difficult to quantify [15]. 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.

5. CONCLUSIONS

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

- Frequency differs significantly between MIIs and MICs for a given motion time-history. As such these events must be considered two different and distinct phenomena.

- 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.

- 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 and potentially more beneficial response, that may be used instead of a fixed support mechanism.

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