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**EVALUATION OF SAFETY PROTOCOLS FOR NASA
AMES/USCG SMALL BOAT RECOVERY EXPERIMENT**

by

Rebecca A. Fosha

June 2018

Thesis Advisor:

Lawrence G. Shattuck

Co-Advisors:

Lyn R. Whitaker

Michael E. McCauley

Second Reader:

Panagiotis Matsangas

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BOAT RECOVERY EXPERIMENT**

Rebecca A. Fosha
Lieutenant Commander, United States Coast Guard
BA, University of Colorado at Boulder, 1996
MA, University of West Florida, 2015

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requirements for the degree of

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June 2018**

Approved by: Lawrence G. Shattuck
Advisor

Lyn R. Whitaker
Co-Advisor

Michael E. McCauley
Co-Advisor

Panagiotis Matsangas
Second Reader

Patricia A. Jacobs
Chair, Department of Operations Research

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ABSTRACT

The United States Coast Guard (USCG) has contracted the National Aeronautical and Space Administration (NASA) to study human performance in a small boat recovery task on the Vertical Motion Simulator (VMS) in Mountain View, CA. Due to safety concerns, participants will be required to wear lanyards connecting them to the simulator structure. Lanyards impart a force on the body and may change postural sway with important effects on performance on the small boat recovery task. The effects of similar lanyards on postural stability in a similar task were investigated in this thesis. Thirty-six participants completed the small boat task on a block (stable platform) or a BOSU balance trainer (unstable platform) with no lanyards, two lanyards (equal force on front and back), or four lanyards (more force on the back than the front). Significant differences in postural sway variability and central tendency were identified for the four-lanyard condition. Subjective fatigue ratings increased during the study but did not correlate to postural sway results. Participants employed different strategies to complete the task and maintain postural stability, suggesting important directions for future research. The results and recommendations from the study were provided to USCG/NASA researchers for use in key decisions for the VMS experiment.

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TABLE OF CONTENTS

I.	INTRODUCTION.....	1
A.	PROBLEM STATEMENT	1
B.	RESEARCH OBJECTIVES.....	2
C.	RESEARCH QUESTIONS.....	2
D.	HUMAN SYSTEMS INTEGRATION	3
1.	System Safety.....	5
2.	Human Factors Engineering.....	6
3.	Personnel.....	7
E.	THESIS ORGANIZATION	7
 II.	 LITERATURE REVIEW	 9
A.	OVERVIEW	9
B.	USCG SIDE DAVIT RECOVERY	9
1.	Operational Evolution.....	11
2.	Simulated Task.....	13
3.	Safety Protocols.....	13
C.	HUMAN PERFORMANCE IN A MOVING ENVIRONMENT	16
1.	Motion-Induced Interruptions.....	16
2.	Proactive Interruptions	18
3.	Measuring MIIs.....	19
4.	MII Models	21
5.	Motion-Induced Interruption Summary	21
D.	POSTURAL SWAY	22
1.	Organization of Postural Control.....	22
2.	Measuring Postural Control in a Moving Environment	25
3.	Postural Sway Summary	26
E.	CONTRIBUTORS TO POSTURAL STABILITY AND TASK PERFORMANCE	27
1.	Learning.....	27
2.	Fatigue.....	28
3.	Personnel Characteristics.....	29
4.	Contributors Summary	30
F.	HYPOTHESES	31
 III.	 METHODS	 33
A.	OVERVIEW	33
B.	PARTICIPANTS.....	33

1.	Selection	34
2.	Demographics	34
C.	MATERIALS AND METHODS	35
1.	Apparatus	35
2.	Block configuration.....	36
3.	BOSU Configuration	37
4.	Lanyards and Personal Protective Gear.....	38
5.	Questionnaires.....	39
6.	Video.....	40
7.	Force Plate	41
D.	PROCEDURES	42
E.	VARIABLES	44
1.	Independent Variables.....	44
2.	Dependent Variables.....	44
IV.	RESULTS	47
A.	OVERVIEW	47
B.	ASSESSMENT OF THE EFFECT OF LANYARDS.....	49
1.	Main Findings.....	49
C.	EXPLORATORY ANALYSIS	52
1.	Learning.....	52
2.	Fatigue.....	53
3.	Personnel Characteristics.....	56
4.	Behavioral Observations	57
5.	Postural Strategy	57
6.	Subjective Assessments.....	59
D.	SUMMARY	59
V.	DISCUSSION	61
A.	OVERVIEW	61
B.	SWAY VARIABILITY (HYPOTHESIS ONE)	62
1.	Results Review.....	62
2.	Relevance to NASA Study	62
C.	SWAY CENTRAL TENDENCY (HYPOTHESIS TWO)	63
1.	Results Review.....	63
2.	Relevance to USCG/NASA Study.....	64
D.	TIME TO COMPLETE (HYPOTHESIS THREE)	64
1.	Results Review.....	64
2.	Relevance to USCG/NASA Research	65
E.	LIMITATIONS	65

VI.	CONCLUSIONS AND RECOMMENDATIONS.....	67
A.	CONCLUSIONS	67
B.	RECOMMENDATIONS.....	67
C.	DIRECTIONS FOR FUTURE RESEARCH	67
	APPENDIX A. QUESTIONNAIRE	69
	APPENDIX B. BORG CR10 FATIGUE RATING SCALE	71
	APPENDIX C. TASK INSTRUCTIONS.....	73
	APPENDIX D. POST-TRIAL QUESTIONNAIRE.....	75
	REFERENCES.....	77
	INITIAL DISTRIBUTION LIST	83

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LIST OF FIGURES

Figure 1.	Key components of the operational evolution	11
Figure 3.	VMS Notional Limits. Source: VMS—Vertical Motion Simulator (2008).	14
Figure 4.	USCG/NASA ICAB setup. Source: VMS Engineering Team Briefing (2017).	15
Figure 5.	Apparatus, shown with Block configuration	36
Figure 6.	Standing surface Block configuration with white tape indicating foot position	37
Figure 7.	BOSU balance trainer centered on force plate and plywood	38
Figure 8.	Researcher demonstrates reaching for the hook with harness and A3P lanyard configuration	39
Figure 9.	Anterior video camera placement (left) and side camera placement with alignment tape (right).	40
Figure 10.	Wall grid	41
Figure 11.	Feet marking with tape in BOSU configuration	42
Figure 12.	Distribution of TTC missing data	45
Figure 13.	Average TTC by participant and platform configuration	48
Figure 14.	Area 95 (in inches) by configuration and lanyard. Vertical lines denote the Standard Error of the Mean.	50
Figure 15.	Means with standard error bars for y avg delta variable (in inches) showing central tendency.	51
Figure 16.	Time to complete trends with standard error bars	52
Figure 17.	Average fatigue levels with standard errors.	55
Figure 18.	Fatigue ratings by participant as a function of order of given fatigue rating	55
Figure 19.	Postural strategies used during the task	58
Figure 20.	Graph plotting averages of the three dependent variables by configuration with standard error bars.	61

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LIST OF TABLES

Table 1.	Sea state table. Source: United States Coast Guard (2013).	10
Table 2.	Quasi random experimental design.....	33
Table 3.	Baseline variability information	49
Table 4.	Test statistics for subjective fatigue ratings between all assessments	54

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LIST OF ACRONYMS AND ABBREVIATIONS

AP	anterior/posterior
A3P	anterior/three posterior
Area 95	area of 95% ellipse
BCM	boat crew member
BMI	body mass index
BOSU	both sides up balance trainer
COM	center of mass
COP	center of pressure
HFE	human factors engineering
HSI	human systems integration
ICAB	interchangeable cab
KSA	knowledge, skills and abilities
MIC	motion-induced correction
MIF	motion-induced fatigue
MII	motion-induced interruption
ML	medio-lateral
NASA	National Aeronautics and Space Administration
OTH	over the horizon
RPE	rating of perceived exertion
TTC	time to complete
UC	unconstrained
USCG	United States Coast Guard
VMS	vertical motion simulator
Y avg delta	difference between trial y average and baseline y average value

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EXECUTIVE SUMMARY

Many maritime activities, including the United States Coast Guard (USCG) deploy small high-speed boats from larger ocean-going vessels to extend mission range and improve mission effectiveness. Launching and recovering these small boats (known as Over-the-Horizon boats, or OTH) are demanding evolutions with more conservative sea state limitations than other operations. The USCG has partnered with the National Aeronautics and Space Administration (NASA) to explore upper sea state limitations on the Vertical Motion Simulator (VMS). NASA engineers and the NASA Human Occupancy Review Board have identified a risk of participants falling off the VMS and proposed fall protection lanyards as the risk mitigation. Fall protection lanyards with self-retracting properties pose an unknown threat to experimental validity through alterations to human postural sway (Cnyrim, Mergner, & Maurer, 2009), which may change human abilities to maintain an upright stance and complete the simulated task (Varlet, Bardy, Fu-Chen, Alcantra, & Stoffregen, 2015; Wertheim, 1996). This study investigates the effect of self-retracting lanyards on postural stability in a shipboard recovery task.

For this study, a laboratory experiment was conducted that involved participants completing a task similar to the task in the USCG/NASA study on a stable (Block) and unstable (BOSU Balance trainer) surface. Three lanyard configurations were evaluated on each surface: unconstrained (UC), an anterior and posterior pair (AP condition), or a single anterior and triple posterior group (A3P condition). Each surface/lanyard configuration set included five replications. A quasi-random design using a Latin square was created, with replications grouped by surface and lanyard configurations due to time constraints. Participants also provided subjective fatigue ratings before beginning the study and at regular intervals throughout. Demographic information such as age, height, weight, active duty status, and fitness activities was also collected. Metrics for postural sway were the variability of sway and the central tendency of sway. The task performance metric was time to complete the task.

Analysis from this study showed that self-retracting lanyards significantly reduced the sway variability on the unstable surface when three lanyards were attached to the

anterior ($p < .001$), and a trend toward reduced variability was identified when only two lanyards were attached. Central tendency of postural sway moved aft with increasing number of lanyards. When an anterior and posterior lanyard were attached (AP), an aft trend was identified for the Block ($p = .067$) configuration. The aft central tendency was statistically significant in the A3P configuration at $p < .001$ for both the Block and BOSU configuration. Time to complete the task was not statistically different between any of the configurations, although the A3P/Block average time to complete was lower than all other conditions. Learning and fatigue effects were not evident in statistical analysis or interpretation of patterns, although subjective fatigue increased over the course of the experiment (p values ranged from .010 to less than .001).

Results from this study informed concrete recommendations for use of fall protection lanyards in the USCG/NASA experiment. Specifically, the study results recommended avoiding fall protection lanyards altogether. Short of that goal, fixed length lanyards were recommended as a preferred solution to the self-retracting type. Finally, a short length center rear lanyard used in this study that caused some interference with a few participants was recommended to be lengthened in the USCG/NASA study. The postural sway data from this study may have implications for future human centered design. The reduction in postural sway may be used in innovative systems design to improve human performance in tasks that depend on postural control. Successful stance strategies identified in future analysis may contribute to postural and task training to improve performance in this and other operations in moving environments. Planned future analysis for the data in this study includes qualitative analysis of observed behavioral strategies toward task completion and postural stability. Results from future analysis will deepen understanding of the results and implications for the boat recovery and other related operational tasks.

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I. INTRODUCTION

A. PROBLEM STATEMENT

The United States Coast Guard (USCG) cutters are capable of deploying small high-speed agile vessels known as Over-the-Horizon (OTH) boats to conduct time critical, long-range missions. OTH boats are considered essential to cutter mission effectiveness, extending the range and mobility of USCG operations in open water. They are limited by the sea state conditions in which they can operate. Launch and recovery sea state limitations impose the greatest constraint on OTH operations. As future systems advance from mission needs statements to operational requirements documents (United States Coast Guard, 2010), requirements writers seek quantitative and empirical data to inform specifications for future systems. Systems engineers have data to bound OTH launch and recovery operations for technological components as a function of sea state, but there is little information on human performance limitations under these conditions. USCG acquisition programs seek to expand the sea state operating conditions for OTH operations; thus better information regarding human limitations is needed. This human performance knowledge gap led the USCG Boat Forces Directorate to initiate an applied research partnership with the National Aeronautics and Space Administration (NASA) Ames Research Center using the Vertical Motion Simulator (VMS) to investigate OTH boat launch and recovery operations.

The goals of the ambitious USCG/NASA project are to study human performance in a simulation of the OTH boat recovery operation, to inform requirements for systems design, and to develop a foundation for future research. The USCG/NASA study will test the hypothesis that OTH recoveries take longer to complete or fail completely in more severe sea states.

To date, the VMS has been an aviation research platform. Human occupants have been contained within an enclosed cabin containing an air vehicle cockpit simulation, and they have been restrained in position via a five-point seat belt to a seat or other fixed hardware element. Naval environment simulations with human occupants who are not restrained or connected to the simulator platform in any way have never been conducted on the NASA

VMS. As a result, a thorough safety review by NASA's Human Occupancy Review Board was conducted including a risk assessment by NASA engineers. Among the identified hazards was the risk of a simulator runaway in one or more of the six degrees of freedom due to a software failure. The likelihood of this risk is difficult to estimate because the motion profiles for the OTH had never been run on the VMS. The risk mitigation strategy suggested for a participant being thrown from the VMS platform was to attach fall protection lanyards from the VMS structure to the participants. From a human performance in motion perspective, haptic connections are known to stabilize the human body in studies of postural control (Cnyrim, Mergner, & Maurer, 2009), but more information was needed to understand how these lanyards would affect the external validity of the USCG/NASA study.

B. RESEARCH OBJECTIVES

The purpose of the present study was to investigate the differences in postural stability between a freestanding human and a lanyard-constrained human to inform the design of the larger USCG/NASA study. Comparisons were made within and between task conditions on a stable surface and on an unstable surface. The study results were provided to the researchers responsible for designing the larger USCG/NASA study. Specific objectives were:

- To determine differences in variability of postural sway with and without lanyards;
- To determine differences in the central tendency of postural sway with and without lanyards;
- To determine differences in task performance parameters between lanyard conditions.

C. RESEARCH QUESTIONS

The research questions addressed by this study were:

- How do lanyards connected at chest level affect postural sway?

- Does time to complete a task change when lanyards are connected at chest level?
- Do lanyards connected at chest level change the subjective experience of completing a task?

D. HUMAN SYSTEMS INTEGRATION

In the introduction to the *Handbook of Human Systems Integration* (HSI), Booher describes HSI as both a managerial and technical concept with objectives to “significantly and positively influence the complex relationships” between people, government and industrial organizations, and design and production methods and processes (2003). The technical and managerial advances of HSI can be seen as an overarching philosophy, embedding themselves within systems engineering and systems management processes (Booher, 2003). HSI embedded early in the systems design process can provide clarity on the cost, performance and human impact of poor decisions, while shedding light on boundaries that define trade space for human-centered performance decisions. Trade-off decisions within this trade space optimize total system performance in materiel and non-materiel solutions and address organizational capability needs (Shattuck, 2018). The USCG envisions HSI as a systematic human-centered approach to total system performance, seeking a cost effective balance among people, hardware and software (United States Coast Guard, 2018a). In the pursuit of these goals, the USCG employs the HSI domains of human factors engineering (HFE), performance and training, manpower and personnel, and system safety. This thesis pertains directly to the domains of HFE, personnel and system safety.

Prior to exploring the HSI domains related most directly to this thesis, two top-level aspects of HSI practice are discussed: HSI-centered (applied) research and trade-off identification and decisions. The progression of the USCG/NASA research proposal from research question to experimental design to the external validity versus safety tradeoff decision exposes some of the more profound challenges of executing HSI. A human-centered approach relies on research efforts to enhance understanding of the complexities of human performance in seemingly endless system performance objectives. The United States Department of Defense (2017) suggests using HSI domains as a guide to identifying science

and technology gaps. In this way, an HSI systems-thinking approach to research can help guide researchers to questions regarding complex interactions between humans and systems. Traditional experimental methods allow for precision in understanding specific processes through strict experimental control of many parameters, leaving only the parameters of interest for examination. However, such controlled settings may have little relevance to operational settings. In contrast, attempting to measure human performance in real-world conditions can be fraught with confounds and render it all but impossible to establish causal (or even correlational) relationships (Barnes & Beevis, 2003). In the USCG/NASA study, there are numerous influences on human performance in a moving environment. Motion sickness, fatigue, anthropometric factors, training and experience top the list of factors that might obscure clarity in the assessment of a maximum sea state. Safety lanyards only add to the complexity and have the potential to obscure meaningful results. In the present study, a more traditional approach was used in order to focus on the effects of lanyards on postural stability. However, practical limitations such as the lack of a motion simulator and limitations of physical space meant that the dependent variables might not correlate directly with the target environment (i.e., the USCG/NASA study or the operational evolution). As Barnes and Beevis (2003) conclude, the role of controlled experiments is to point to critical design decisions for consideration, and important crew-related factors that need to be investigated. A focused, controlled experiment will cover a small area of the response surface directed at the most critical factors (Barnes & Beevis, 2003). The present study seeks to cover the postural impact of safety lanyards in order to inform the critical safety decision for the planned USCG/NASA venture.

An important top-level HSI concept is integration of human-centered design across the HSI domains in order to optimize total system performance. A consequence of interdependent relationships between domains is that improvements in one domain may result in adverse effects in another domain (United States Department of Defense, 2017), or with other aspects of system performance (Barnes & Beevis, 2003). In the simplest form, tradeoffs may appear to be binomial, but complexity lurks in complex systemic interactions. In the case of the USCG/NASA study, experimental validity can be seen as the system performance parameter, while system safety is the HSI domain tradeoff. Careful evaluation

of the viable alternatives by NASA led to a programmatic decision to employ safety measures that may obscure important information sought by USCG decision makers. In systems acquisition HSI-centered activities, tradeoffs are quantified in terms of cost and system performance (Barnes & Beevis, 2003). The present study sought to evaluate the selected tradeoff alternative in terms of experimental performance cost in an empirical way: implications for the primary dependent variable in the USCG/NASA study.

The methodology to accomplish integration of domain-specific advances in systems design is outlined by O'Neil (2014) in a human-technology integration model. This model regards matching systems affordances and constraints to human capabilities and limitations as the manner by which HSI can be accomplished. Total system performance can be seen as relationships between all four parameters. Thus, where human limitations, capabilities and systems constraints are optimized, system performance is dependent on system affordances. In the case of the OTH recovery problem investigated by the USCG and NASA, ship hull design is a well-trod path in the search for system affordances in response to the constraint of sea motion. Little is known about human limitations while conducting small boat recoveries at high sea states, thus humans are left to fill in the gap with their capabilities. In the present study, unknowns in both system performance constraints (motion profile software reliability) and human capabilities (performance in high sea states on the VMS) have led to a conservative risk analysis (lanyards, with an unknown impact on total system performance). The present study sought to identify proposed system design impacts on human capabilities such that the USCG/NASA study can more accurately evaluate human limitations in the OTH task.

1. System Safety

System safety design characteristics serve to minimize the potential for mishaps leading to system damage or destruction, or bodily injury or death (United States Coast Guard, 2018b). There is some overlap with the survivability domain, which includes system design features that allow the crew and the system to survive natural environments (United States Department of Defense, 2017). This domain is applied to engineering and management criteria and techniques throughout the life cycle, with the familiar goal of cost-

effective accomplishment of system objectives (United States Coast Guard, 2018b). In the case of the OTH human performance question, environmental hazards such as high amplitude complex motions, motion interactions between OTH and cutter (abrupt “slam” motions), and associated weather conditions such as high winds and precipitation lead to unacceptably high levels of risk for injury. These risks prevent exploration of sea states above the present limit of sea state 4. Although simulation parameters allow exploration of more severe motion profiles, the use of human participants still poses limitations due to safety concerns. Thus, while safety and survivability are primary concerns in the USCG/NASA study, safety also generated the most consequential tradeoff discussions. Evaluation of the safety measures proposed by NASA is a primary focus of the present study.

2. Human Factors Engineering

Most definitions of the HFE domain focus on integration of human capabilities and limitations into system design, development, test and evaluation, and modification of systems to maximize the ability of humans to operate, maintain and support a system for total system performance (United States Coast Guard, 2018a). The USCG adds the following organizational systems design goals to HFE: minimal manpower, effective training, habitability and suitability, and survivability (United States Coast Guard, 2018a). In the shipboard launch and recovery evolution, HFE most closely aligns with naval engineering goals for OTH operations in higher sea states. The present study sought to contribute to the collective knowledge of motion-related postural stability by exploring postural stability on an unstable surface with restraining forces applied to the body at chest height. Along these lines, the fundamental purpose of this study was to inform the USCG/NASA research team regarding changes to postural stability imposed by safety lanyards. If no differences were found, the USCG/NASA study could proceed with cautious optimism that the lanyards do not add to the list of possible experimental confounds. If differences were found, then the USCG/NASA researchers would have to consider alternative approaches to ensuring participant safety without compromising experimental validity.

3. Personnel

The personnel domain includes the range of knowledge, skills, abilities and experience levels necessary to perform the job successfully (United States Coast Guard, 2018a) This domain includes performance and anthropometric characteristics of the user population (United States Department of Defense, 2017). Human performance characteristics for current and projected systems and operational specialties are included in the definition. The personnel domain is closely related to the manpower domain (the number of skilled personnel necessary for system operation, maintenance and support) in that workload changes based on knowledge, skills and abilities (KSA), and a high workload per person implicates higher manpower numbers for total system performance. Physical attributes of participants via the personnel domain were another focus of this study. Important differences due to physical characteristics may yield insight into postural control strategies, and varying effects of lanyards on postural stability. For example, a taller person may experience different postural control challenges from forces imposed at chest height than a shorter person. This information may have necessitated a change in how NASA approached lanyard length and safety zones in the VMS experiment.

E. THESIS ORGANIZATION

This thesis is organized into six chapters. This chapter provides the problem statement, objectives, research questions and the HSI perspective relevant to this study. Chapter II explores the literature related to the research questions, hypotheses, and expected outcomes. Chapter III covers the participants, apparatus, research design and procedures of the study. Chapter IV presents the results of the data analysis and major findings of the study. Chapter V discusses the implications of the major findings in terms of hypotheses, HSI domains and trade space opportunities. Chapter VI provides conclusions and makes recommendations for future research.

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II. LITERATURE REVIEW

A. OVERVIEW

The literature review is divided into four main sections. The first section explores the operational evolution that is the focus of the USCG/NASA study, its simulated counterpart, and the proposed safety protocols. The second section traverses the literature from studies of postural stability in a moving environment that are the basis of analysis for the USCG/NASA study to the contribution of postural sway to stability. The literature reviewed in this section provides support for the experimental design of the present study. The third section discusses explanatory variables that are known to be important contributors to human performance in a moving environment and postural stability. The final section concludes with the hypotheses and expected outcomes of the research.

B. USCG SIDE DAVIT RECOVERY

Numerous international military and maritime activities possess the ability to deploy a high-speed, agile small boat from a larger, open-ocean vessel. This capability supports nearly all USCG missions and extends the effectiveness of USCG Cutters in open seas. The subject of this study is the 26-foot OTH, which is launched from the side of USCG cutters ranging in size from 210 to 378 feet long (United States Coast Guard, 2016). At the completion of a mission, the OTH comes alongside a cutter to be hoisted by two cranes known as davits into a cradle for storage. Known as a side davit recovery, a subset of this activity is considered in the USCG/NASA study. The subset involves a service member (with a qualification known as boat crewmember or BCM) standing or kneeling on the bow of the OTH, reaching up and grasping a hook lowered from the cutter davit, and connecting it to a lifting eye on the bow of the OTH (United States Coast Guard, 2013). A team coordinates the entire recovery process with commands issued to the crewmember, usually by the OTH coxswain. The side davit recovery is the most hazardous evolution an OTH crew encounters with respect to sea motion; as a result, the sea state limits for this evolution are the most restrictive among all OTH missions. As an example, the OTH-IV is limited to 11-foot seas for transit operations with no surf (United States Coast Guard, 2016), but launch and recovery

limits in most cases are not recommended above six to eight foot seas (United States Coast Guard, 2013). These translate to sea state five and four respectively in the Davis Sea State scale as shown in Table 1.

Table 1. Sea state table. Source: United States Coast Guard (2013).

Beaufort Height Scale	Wind Speed(Knots)	Indications	Approximate wave height		Davis Sea State
			(Feet)	(Meters)	
0	Calm	Mirror Like	0	0	0
1	1 to 3	Ripples with the appearance of scales	0.25	0.1	0
2	4 to 6	Small wavelets that do not break. Glassy appearance	0.5 to 1	.2 to .3	1
3	7 to 10	Large wavelets. Some crests begin to break. Scattered white caps	2 to 3	0.6 to 1	2
4	11 to 16	Small whitecaps becoming longer. Fairly frequent white caps	3.5 to 5	1 to 1.5	3
5	17 to 21	Moderate waves. Pronounced long form. Many whitecaps	6 to 8	2 to 2.5	4
6	22-27	Large waves begin to form. White foam crests are more extensive. Some spray. Coast Guard definition of heavy weather (8 feet, 30 Kts)	9.5 to 13	3 to 4	5
7	28 to 33	Sea heaps up. White foam from breaking waves begins to blow in streaks along the direction of the waves	13.5 to 19	4 to 4.5	6
8	34 to 40	Moderately high wave of greater length. Edges of crests break into spindrift foam blown into well-marked streaks in the direction of waves.	18 to 25	5.5 to 7.5	6
9	41 to 47	High waves. Dense streaks of foam. Sea begins to roll. Spray affects visibility	23 to 32	7 to 10	6
10	48 to 55	Very high waves with over hanging crests. Foam in great patches blown in dense white streaks. Whole surface of sea takes on a white appearance. Visibility affected	29 to 41	9 to 12.5	7

Excerpted from the USCG shipboard launch and recoveries manual. Davis Sea States three through five in bold are the focus of this study.

The BCM at the bow of the OTH is exposed to greater motion than other positions on the boat (Stevens & Parsons, 2002). While cutter crews maneuver to provide a lee (shelter from the wind) and minimize the pitch and roll (United States Coast Guard, 2013), the BCM may still be exposed to complex sea motions that present challenges to postural stability. Consequently, hook retrieval and connection to the OTH is the most hazardous task in the side davit recovery activity.

1. Operational Evolution

The side davit recovery activity (United States Coast Guard, 2013) commences with a series of briefings among all parties involved in the recovery task. These briefings include a “Green Amber Red” risk assessment briefing (United States Coast Guard, 2003). The boat deck captain stationed on the cutter oversees the operation and gives orders to the davit operators who manually control the speed of the hook as it lowers to the OTH. The coxswain is responsible for steering the OTH and giving commands to and on behalf of the boat crew; the BCM is responsible for grasping the hook as it is lowered from the davit and connecting it to the lifting eye (Figure 1).

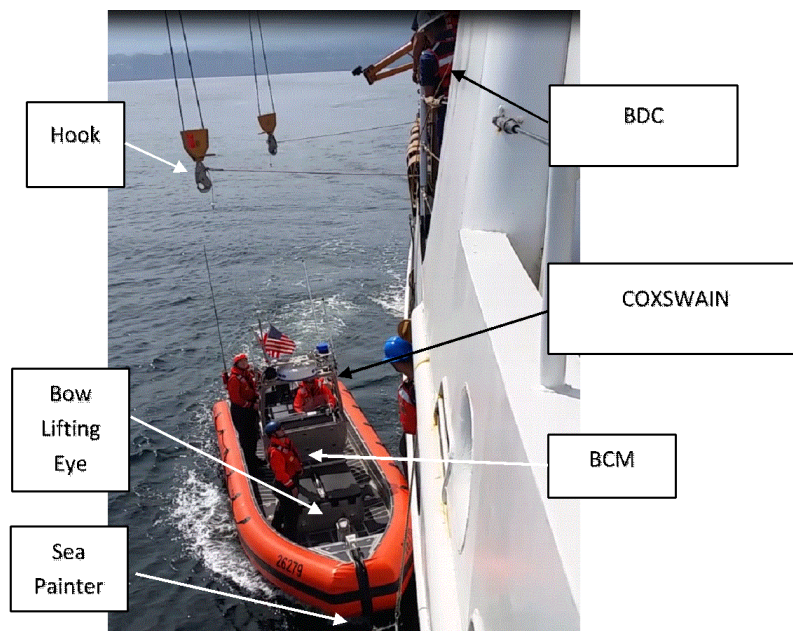


Figure 1. Key components of the operational evolution

Once the briefings are complete and the cutter is on the most beneficial course and speed, the OTH makes an approach to the cutter. When the OTH is stable alongside the cutter, the BCM on the OTH retrieves and connects a line (the sea painter) to the bow of the OTH. Once connected, the coxswain reduces power to allow the sea painter to become taut, the OTH boat is pulled along by the cutter and “rides” the cutter motion. This stabilizes the fore and aft relative motion of the OTH and reduces the workload of the coxswain to stabilize the lateral motion between the two vessels. Once this position is established, the coxswain reports “ready in the boat.” During the approach, the BCM is typically standing or sitting near the bow of the boat, depending on the intensity of the sea motion. Once “ready in the boat is announced,” the BCM assumes an upright posture (standing or kneeling) near the lifting eye to retrieve the hook when it is lowered. At that time, the boat deck captain commands the davit operator to “send down forward” or begin lowering the hook to the OTH. The davit operator lowers the hook toward the small boat by way of the davit mechanism (not visible in Figure 1), making progressively smaller corrections and attempting to match the OTH movement with the hook. The BCM retrieves the hook, and once the hook is within range of the lifting eye, the coxswain gives an order to “hook forward” which cues the BCM to connect the hook to the forward lifting eye, followed by “hook aft” cueing a BCM on the stern of the OTH to do the same once the forward hook is attached. Thereafter, the boat deck captain coordinates with the deck crew to appropriately position the davits and begin winching the OTH out of the water (United States Coast Guard, 2013). Images of the operational evolution are shown in Figure 2. The left pane shows the forward BCM reaching to grasp the hook and the right pane shows the aft BCM connecting the hook to the lifting eye.

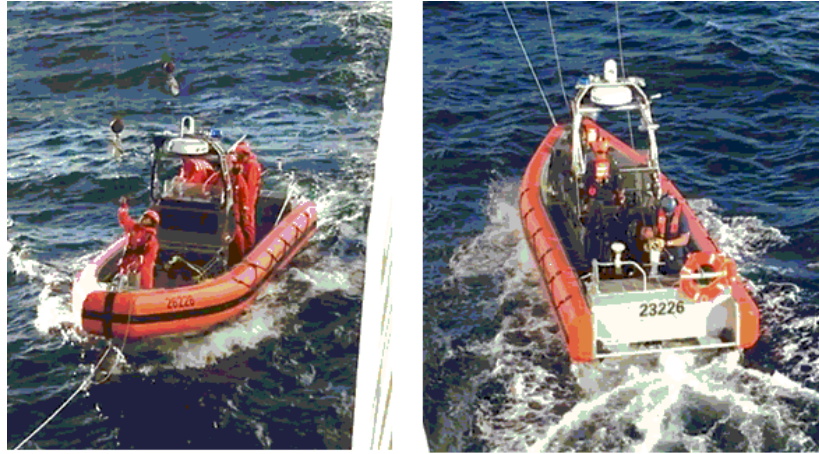


Figure 2. Images of the operational task

2. Simulated Task

The simulated task for the USCG/NASA study was selected based on the postural hazards faced by the BCM standing at the bow of the OTH, between the command to “send down forward” to the hook attachment when the BCM can retreat to a more secure location on the OTH. This segment is important because once the command to “send down forward” has been given; the BCM must gaze upward toward the descending hook. He or she must also be ready to grasp the hook with both hands when it is within reach, and can no longer hold on to the OTH structure or the lifting eye in heavy seas. Once the BCM has his or her hands on the hook, postural stability is influenced, at least to some degree, by the hook as it is guided to the lifting eye.

3. Safety Protocols

The device selected to simulate the OTH side davit recovery task is the Vertical Motion Simulator (VMS), a NASA Ames Research facility in Moffett Field, California. The VMS is a high fidelity, six degrees of freedom, full motion simulator that can simulate low frequency, high amplitude motions (De Los Santos, 2017). At over 40 feet of vertical travel and 30 feet of horizontal travel, it is one of the most capable full motion simulators in the world. Operational limits to the VMS are shown in Figure 3.

NOMINAL OPERATIONAL MOTION LIMITS*			
Axis	Displacement	Velocity	Acceleration
Vertical	±22 (ft)	15 (ft/s)	22 (ft/s ²)
Lateral	±15 (ft)	8 (ft/s)	13 (ft/s ²)
Longitudinal	±3 (ft)	4 (ft/s)	10 (ft/s ²)
Roll	±14 (deg)	40 (deg/s)	115 (deg/s ²)
Pitch	±14 (deg)	40 (deg/s)	115 (deg/s ²)
Yaw	±20 (deg)	46 (deg/s)	115 (deg/s ²)

*Maximum cockpit weight on beam: 15,000 lb

Figure 3. VMS Notional Limits.
Source: VMS—Vertical Motion Simulator (2008).

To date, the VMS has only been used for aviation simulations, from military rotary wing to commercial airliners, to space vehicles such as a lunar lander and the space shuttle. Participants in all of the aviation simulations were secured in a seated or standing position with a five-point seatbelt system, and fully enclosed in an interchangeable cab (ICAB), simulating the vehicle structure and cockpit. For the USCG/NASA study, an ICAB was modified to recreate the OTH hardware and scenario (Figure 4). Safety measures on the ICAB include a three-foot high railing with poly-carbonate sheeting, a safety switch accessible to the participant to abort the motion of the platform, a helmet with face shield, headset with audio microphone, knee pads and gloves, and lanyards connecting the participant to the fixed cab. The proposed lanyards were self-retracting, with a light force imparted on the body from roughly 1.8 pounds of force in a static condition to greater than 2.0 pounds with extending accelerations. Abrupt accelerations on the lanyard lock an inertia reel mechanism, preventing additional lanyard from reeling out. Alternative lanyards may be fixed length, restricting human movement at the edge of the ICAB envelope and preventing contact with the ICAB structural elements. Multiple lanyard configurations were considered. The most restrictive configuration was one with four self-retracting lanyards in the positions shown in Figure 4. Other alternatives included a single self-retracting lanyard centered in the chest (anterior) and back (posterior), fixed length

lanyards in anterior and posterior side positions with a single self-retracting in the center posterior position, or four fixed length lanyards.

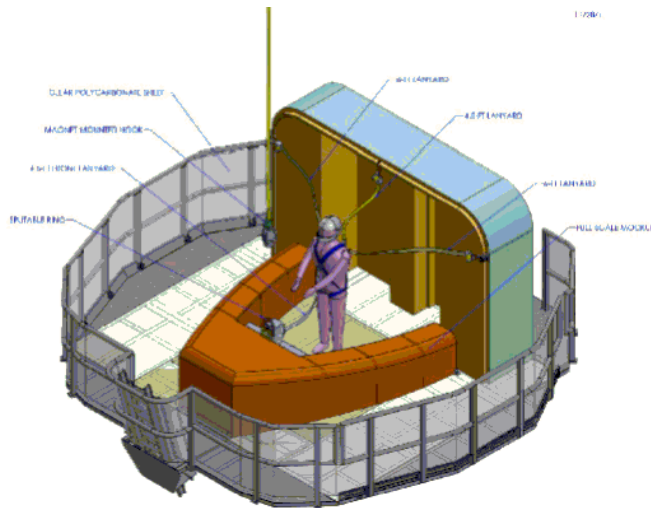


Figure 4. USCG/NASA ICAB setup.
Source: VMS Engineering Team Briefing (2017).

Returning to the operational evolution, it is thought that the position of the service member as he or she attempts to grasp and connect the hook creates the greatest risk in high sea states. During this phase of launch and recovery, the service member is most vulnerable to motion imposed by the ocean, which can disrupt attention, balance or both, interfering with task performance. These disruptions are known as motion-induced interruptions (MII). Forces imposed on the torso, or abrupt jerks on the body may interrupt natural compensation for external motion stimuli and obscure important observation of the true effects of high sea states. The introduction of artificial physical attachments to the body may introduce differences in how a BCM maintains balance in the experimental environment and the real world, reducing the external validity of the research. There is no known research that would provide estimations of the effect of the chosen lanyard configuration on the experimental results. This thesis fills the gap and provides some evidence of the effect of self-retracting lanyards on human postural stability.

C. HUMAN PERFORMANCE IN A MOVING ENVIRONMENT

Drawing the connection between the USCG/NASA study and the thesis research requires a review of the literature regarding human performance in a moving environment. This discussion spans early definitions of MIIs, modern concepts of proactive MIIs, measurement methods, and two models for MIIs, which provide a basis for understanding postural sway as a component of stability in a moving environment.

1. Motion-Induced Interruptions

In an early study of MIIs, Applebee, McNamara and Baitis (1981) administered a survey during sea trials of a USCG cutter in which personnel on board the cutter reported the effect that ship motion had on their ability to perform their duties. On the same survey, department heads on the cutter assessed reduced speed, quality and accuracy of work within their departments. Subsequent work by the same researchers initiated an early definition of an MII as an

occurrence of unavoidable circumstances when ship motion-induced forces produce instabilities in the person's stance, which can only be countered successfully by either holding on to some part of the ship, or by significantly altering the posture to re-establish personal stability. (Baitis, Applebee, & McNamara, 1984, p. 195)

In the 1984 work, ship motion time histories were generated in the Navy Standard Ship Motion Program and the movements of two crewmembers walking underneath a hovering helicopter were modeled using simulation software. The combined data (time histories and simulation information) allowed them to estimate the lateral accelerations that would cause one or more MIIs. They used a lateral force estimator, which was a “combination of earth referenced acceleration and ship referenced lateral acceleration due to ship roll” (Baitis, et al., 1984, p. 195). The lateral force estimator values they presented regarding MII frequency ranged from 0.08g (MIIs are possible under these conditions) to 0.16g (extremely hazardous, four or more MIIs per evolution). They focused on the significance of MIIs in compromising crew safety and note that crew “skill or luck” was not assessed, indicating that there is more to postural stability than measuring the effects of motion on a stationary object. They elaborate that skill may involve purposefully sitting down or

allowing a fall to occur during severe MII conditions rather than struggling to maintain stable footing. In the task they analyzed, this skilled action would avoid tumbling toward or off the side of ship (Baitis, et al., 1984).

MIIs were further defined when Graham developed mathematical calculations for predicting MIIs, which he couched as “loss of balance events.” The human component of the calculation was half the stance width divided by the height of the center of gravity above the deck (Graham, 1990). Even though the method was an important advance in human performance research for its time and has been referenced extensively since, it has limitations. First, Graham’s equation overestimated MIIs in validation studies (Crossland & Lloyd, 1993; Crossland & Rich, 2000). Second, it fails to consider postural compensation for motion (Gehl, 2013), motion frequency or complexity (Matsangas & McCauley, 2013). Nonetheless, Graham’s tipping equation provided a useful metric for ship designers to estimate the effect the unique motion signature of a vessel would have on the operators therein, and thus it represented a great advance in ship design.

Crossland and Lloyd (1993) advanced the definition of MIIs as a “slide, stumble or loss of balance countered only by task abandonment to keep upright” (pp. 11–12), introducing the concept of task abandonment as an explicit component of MIIs. Crossland and Rich expanded on this definition in 1998, explaining that making postural adjustments is the reason for task abandonment (Crossland & Rich, 1998). In 2000, they transformed “task abandonment to make a postural adjustment” (1998) to “abandon[ing] their allotted task to pay attention to keeping upright” (Crossland & Rich, 2000, p. 2). Two subtle shifts in this definition hint at the true complexity of MIIs. First, task abandonment may be due to an attentional shift instead of, or in addition to, a loss of balance. Second, the MII may occur in order to keep upright, indicating a human pre-emption of loss of balance (Langlois, MacKinnon, & Duncan, 2009; Wedge & Langlois, 2003).

In the mid-1970s, an important study on task performance metrics in moving environments was conducted. The Office of Naval Research conducted a two-year study investigating surface-effect ship motions and task performance. Malone (1977) investigated tasks such as navigation plotting, lock opening, keyboard operations, and tracking and equipment maintenance and repair, nearly all completed in a seated position.

They found performance decrements in some, but not all of the tasks. Furthermore, when motion sickness was not a factor, the participants were able to conduct these tasks with “reasonable proficiency.” The experimental condition in this study lasted up to 48 hours. Task performance was found to improve with duration of exposure, indicating the presence of adaptation to the motion in task completion. They were unable to score the gross motor task they studied objectively because they could not account for the participants’ propensity to work harder at the task to compensate for motion interference (Malone, 1977).

McLeod, Poulton, Du Ross and Lewis (1980) studied manual control skills in both standing and seated positions, with arms supported, restrained or free moving. They gave their participants substantial practice before performing the tasks in motion conditions. They found serious performance reductions in a tracing task with unsupported arms and a smaller, but still significant, reduction in performance in a tracking task with arms supported by restraints. They did not find performance changes in a keying task (McLeod, et al., 1980). Crossland and Rich studied several stance directions and tasks. They found that the duration of MIIs while standing with arms overhead were higher than standing alone, conducting a manual lifting task below shoulder height, or conducting a number recognition task (Crossland & Rich, 2000). These studies of task performance in motion conditions suggest that MIIs and MII duration are task specific and can improve with repeated exposure to the motion condition.

2. Proactive Interruptions

Modern researchers have sought to enrich our understanding of human performance in a moving environment by examining the complexities of human performance in that environment. A human-centered approach necessitates revisiting skill (Baitis, et al., 1984), postural compensation (Gehl, 2013; Graham, 1990), and adaptation (Malone, 1977). Holmes et al. (2005) introduced a novel definition of MIIs that centered on what happens before a loss of balance event: “A MII is defined when a person has to temporarily abandon the task or else execute alterations in the base of support in order to maintain balance” (p. 323). In subsequent work, they developed this concept into a motion-induced correction

(MIC). Where an MII is a motion perturbation event requiring an operator to cease an activity and move feet to maintain balance, an MIC precedes an MII, and is a proactive strategy to adjust stance or support before an anticipated motion perturbation, thus minimizing the risk of losing of postural stability (Duncan, et al., 2013). These concepts expand the scope of MII research and may yield insight into the effects of experience, habituation, and individual physiology (Duncan, et al., 2013). Another group of researchers expanded the scope of MIIs to “probable MIIs” to account for human interaction with the environment (Matsangas & McCauley, 2013). These researchers measured minor movements such as a slight lifting of the heel as a probable MII. They found that probable MIIs are more common than loss of balance events (traditional MIIs) on the order of 16% to 67%. The MIC suggests an explanation for the frequency of probable MIIs reported by Matsangas and McCauley: anticipatory actions to avoid loss of postural stability.

MICs or probable MIIs may involve control of attention between three priorities: the task to be completed, pre-emptive postural action to maintain balance (while continuing or briefly pausing the task), and a complete attentional and physical diversion to reactive postural actions with a loss of attention on the task. The range of options available to the novice in a moving environment would be limited, spanning a continuum from no motion-driven balance problems to a complete attentional diversion to balance due to motion. The responses a novice offers to motion perturbations may be more reactive in nature. With cumulative exposure to motion perturbations, learning may occur in the form of adaptation (learning to respond to a specific moving environment) and habituation (learning to work in a moving environment in general). Adaptation and habituation would increase the range of response possibilities through improved sensation and anticipation of motion and sensory cues, predicting motion perturbations, and directing the body to an array of proactive corrective actions.

3. Measuring MIIs

Techniques for measuring MIIs are suggested in the literature. Measurement of task completion and other measures may be applied to understand how motion interrupts task performance (McLeod, et al., 1980). Crossland and Lloyd suggest using both objective

(motion causing the MII) and subjective (observation of the MII) event markers to denote when an MII has occurred. The events up to four seconds prior the MII must be examined for the possible cause of the MII (Crossland & Lloyd, 1993). That time frame may also be relevant to observing probable MIIs or MICs. Movements specific to the task may indicate more susceptibility to MIIs or a change in the nature of the MII (Crossland & Rich, 2000). The duration of an MII, or the time that a person is not actively engaged with the task, may be an additional indicator of performance decrement, and MII severity (Crossland, et al., 2007). Increased duration of one MII may result in an additional MII before posture is recovered and the task can be resumed. In high motion states, the task may be abandoned altogether in favor of one long MII, preserving survivability in the motion condition.

A study conducted by Crossland et al. (2007) included two trials: one conducted in moderate seas and one conducted in rough seas (Davis sea state 4 and 6 respectively). Although the aim of their study was to validate an MII model derived from empirical data (Crossland & Lloyd, 1993) and their statistical methods were not reported, their results provide some insight into the complex nature of MIIs. Although the sample size in the study was small ($n=5$), the mean tipping coefficients for four out of five tasks was higher (more stable) at sea state 6. If missing data are ignored, two out of three tasks (both manual handling tasks) yielded more stability in a higher sea state. Their MII duration data shows a similar trend. The MII rate (total number of MIIs/min) for both manual handling tasks was similar in both sea states. As the researchers point out, the subjects in their study were permitted to adopt a solid stance to counter the weight of the handling tasks (Crossland, et al., 2007). One possible explanation for the surprising results is that the humans took a more proactive stance in higher sea states because they were anticipating severe postural disruptions, thus protecting themselves from unexpected stand disturbances and allowing them to focus more on task completion. That is, human skill and strategy in the form of proactive intervention moderated the effect of the severe sea state motion on human balance.

4. MII Models

The earliest model developed to predict MIIs was Graham's rigid body model (Graham, 1990), which was found to overestimate MIIs (Baitis, et al., 1984; Crossland & Rich, 1998). This is due to its simplistic and mechanistic approach to an interaction in which a human can make adjustments to avoid MIIs (Duncan, et al., 2013; Matsangas & McCauley, 2013). An alternative model that has been suggested is the inverted pendulum model, which seeks to capture the salient motion features of a complex at-sea environment, while minimizing complexity of the model (Langlois, et al., 2009; Wedge & Langlois, 2003). Adjusted to account for the complexities of sea motion, this model shares parameters with the inverted pendulum model common to postural research (Asai, et al., 2009; Weaver, Glinka, & Laing, 2014). Common metrics include the center of pressure (COP), acceleration at the center of mass (COM), and inertia of the body about the effective joint center of the combined ankle system, weight of the body (without feet) and COM height above the ankle joint (Weaver, et al., 2014). Although this model had some advantages over the rigid body model, problems with tuning a constant in the mathematical formula led to either over- or under-predicting MIIs (Langlois, et al., 2009). The authors suggest that individual differences in MII occurrence, to include the occurrence of MIIs when ship motion did not seem significant enough to cause one, may account for the discrepancies between the model predictions and measured MIIs at sea. Recent works have challenged the inverted pendulum model, suggesting instead that postural activity is more like a non-linear system (Schweigart & Mergner, 2008), with in-phase and antiphase patterns relative to perturbation stimuli. For a full discussion, see (Bardy, Oullier, Lagarde, & Stoffregen, 2007).

5. Motion-Induced Interruption Summary

Motion-induced interruptions are the most common object of study in research on human performance in a moving environment. Modern definitions of MIIs include physical changes in stance or other physical actions to stay upright and attentional diversions that delay task performance. Adaptation to motion conditions changes the nature of MIIs with increased exposure to external motion. Task-specific learning also changes task

performance metrics with secondary effects on MIIs. Recently researchers have focused their study on proactive MIIs (MICs and probable MIIs) in an attempt to improve understanding of human interaction with the moving environment. Attentional priorities among task completion, proactive responses to motion, and reactive responses may vary with task and motion experience.

MIIs are often measured by type, number and duration. Several models have been developed to help researchers and ship designers predict MIIs and design better systems. Graham's tipping equation is a mechanistic approach that often over-predicts MIIs due to human intervention, including proactive MIIs, which are not included in the model. The inverted pendulum model connects postural stability research to the moving environment by considering more parameters and capturing more of the features of complex motions, and provides a basis for the connection between postural stability performance in a moving environment.

D. POSTURAL SWAY

The literature in this section introduces some fundamental characteristics of postural stability, supporting the use of postural sway as the basis for investigating the influences of safety lanyards on postural stability and MIIs in the USCG/NASA study. The literature review presented here is not exhaustive, as postural stability research extends into the realms of human performance in sports, rehabilitation, pathology, cognition, and sensation and perception, among others. The intent of this section is to provide a general understanding of postural sway and how it relates to the study of human performance in a moving environment.

1. Organization of Postural Control

Contrary to the literal meaning of the words, at the micro level, natural postural stability is actually not very stable. The maintenance of balance requires constant adjustments to body segments even when the external environment is completely stable; these subtle movements are known as postural sway (Strang, Haworth, Hieronymus, Walsh, & Smart, 2011). Postural sway has two main elements: a high frequency/low amplitude component tuned around a lower frequency/high amplitude central tendency

(Metcalf, 2005). The movement of the central tendency of postural sway is thought to involve an estimation process of a desired reference position based on the current environment. The higher frequency sway movements are seen as an oscillatory feedback process allowing constant assessment of the current posture against the desired reference position (Metcalf, 2005). Postural sway has been found to be greater in the front and back direction relative to the body (anterior/posterior or AP) than the left and right direction (medio-lateral or ML) when standing on a stable surface (Chen & Stoffregen, 2012). This may be due to greater joint mobility in the AP direction, and may be reflected in the tendency to choose a stance width that is wider than the feet are long when striving to maintain stability.

Postural sway has been shown to be tuned to elements of the environment. For example, in a study of infant bouncing in “jolly jumpers,” an initial sporadic phase of motor action assembly was followed by a “tuning phase” characterized by a steady decline in the period of bouncing, to a resonance phase, where bouncing reached a resonant period with further decreased variability (Goldfield, Kay, & Warren, 1993). Development of postural sway over the life span demonstrates an increasingly complex tuning of postural sway. In a study by Ashmead and McCarty (1991), there was evidence of frequency-dependent coupling tuning of postural sway to visual stimuli in adults, which was particularly strong at the 0.2-0.3 Hz frequency range. At higher or lower frequencies, phase locking between sway and visual stimuli occurred, but was interrupted by a loss of the coupling, followed by increased variability (either phase lead or lag) until phase locking was re-established (Dijkstra, Shoner, Giese, & Gielen, 1994). This indicates that there may be an ideal frequency for postural sway given the mass of the human body and capabilities of the sensory-musculoskeletal control system. The frequencies where Ashmead and McCarty found the most consistent motion/postural synchrony are very near the frequency range where motion sickness has been shown to be the most profound (McCauley, Royal, Wylie, O’Hanlon, & Mackie, 1976). Subsequent research has investigated synchrony of postural sway to a moving environment as a possible predictor of motion sickness at sea (Bos, 2011).

Postural sway is a dynamic and multi-sensory process. For example, Metcalfe (2005) found that over the course of the first year of independent walking, the magnitude of sway variance remained the same, while the time between maximal variance (central tendency) excursions increased. He also found that both parameters decreased when the infants had access to a touch surface. In adults, a touch surface reduced variability in sway but the timing of sway excursions was not changed (Jeka, 1997; Jeka, Oie, Schoner, Dijkstra, & Henson, 1998) suggesting that in adults, optimal sway timing has already been achieved. In this case, touch surfaces support sensory processes to identify the desired reference position, reducing the need for a feedback process to find it. Studies of visual inputs to postural stability lend more insight into the subject. In a study comparing the postural sway of infants and adults in light and dark conditions, infants were found to have more overall sway variability, but no differences between light and dark conditions, whereas adults had significantly more sway in dark conditions (Ashmead & McCarty, 1991). They suggest that the early regulation of standing posture does not rely on visual information. Taking this conclusion one step further, this also may indicate that adults have learned to integrate visual sensory information into their compensatory postural paradigms and suffer a degradation of postural control when visual information is removed. Together, these studies demonstrate the complex sensory processes that regulate postural sway and upright stance that are influenced by any sensory input changes.

Few studies could be found that investigated the effects of force applied to the torso on postural sway. An exception is a group of researchers who conducted a series of studies to investigate the development of a multisensory model for postural control (Cnyrim, et al., 2009; Maurer, Mergner, & Peterka, 2006). They were primarily interested in expanding the body of knowledge on the sensory inputs to postural control; they used external pull forces to understand how force-related sensory information contributes to upright stance. They found that when pull forces were combined with a sinusoidal motion stimulus, participants assumed a counter-leaning body position compensating for the pull stimulus (Maurer, et al., 2006). In a subsequent study, they found that force cues were advantageous for stability, added redundancy to postural stability sensory inputs, and improved the overall flexibility and robustness of the postural stability system (Cnyrim, et al., 2009). The

participants in that study had a persistent conscious awareness of the sensation of the pull forces on their body, indicating there was some degree of conscious cognitive processing in addition to automatic postural responses (Cnyrim, et al., 2009). Thus, it is reasonable to hypothesize that lanyards imposing a pull force on the body will alter how participants in the USCG/NASA study maintain postural control under motion conditions and may have implications for task performance.

2. Measuring Postural Control in a Moving Environment

Recently, researchers have been looking to connect tuning of postural sway to motion conditions. Tuning of postural sway to irregular motion conditions is of particular interest to investigators concerned with work done in the naval environment. Ooteghem et al. (2008) investigated tuning postural sway to random or regular motion perturbations generated by a motion platform. In their study, they investigated motion with regular frequency, varying the amplitude of the motion. Their participants were in either the random amplitude or a regular amplitude group. They measured COM displacement and phase relative to the motion platform. In both the random and the regular group, they found a reduction in phase variability over the course of the trials, which was sustained in a second day of testing (Ooteghem, et al., 2008). Their findings suggest that tuning of postural sway occurs regardless of the predictability of motion, but overtime a type of motion pattern learning occurs. Varlet, Bardy, Chen, Alcanatra and Stoffregen (2015) took the next step and investigated postural way and coupling at sea. In order to overcome challenges comparing body position to ship motion accelerations, they employed accelerometers on both the body and the ship deck. They found that that coupling of postural sway with ship motion occurs, and that it is associated with the alignment of the axis of the body as compared to the axis with the ship. Other areas of inquiry related to postural sway and shipboard motion include task performance (Chen & Stoffregen, 2012) and motion sickness (Bos, 2011; Stoffregen, Hettinger, Haas, Roe, & Smart, 2000).

When sea trials are not possible, and motion platform research is not practical, an alternative methodology to study postural stability is to introduce instability through an unstable surface. In their review of methods of introducing postural perturbations, Bardy,

Oullier, Lagarde and Stoffregen (2007) noted that many experimental perturbation methodologies have been used as alternatives to external movement from a motion driven surface (motion simulator). Postural perturbations (instability) can be introduced via an unstable surface, a moving visual display, a task to be completed, and even varied conversation partners; all have been found to relate to changes in postural activity. They assert that “an external stimulus to the postural system counts as a perturbation only if the person’s goal is to stabilize posture relative to that stimulus” (Bardy, et al., 2007). By their reasoning, if a task completion goal requiring stabilization is introduced, an unstable surface is a suitable method to study postural instability.

A common validated tool to measure postural stability is a force plate, which measures the center of the distribution of the total force of the body (including body weight and inertial effects of body movement) (Golriz, Hebert, Foreman, & Walker, 2012). Murray, Seireg and Sepic (1975) used a force plate to study postural stability and steadiness of three generations of men, finding large excursions in the lateral center of pressure during standing on two feet, leaning and standing on one foot. The central tendency of the excursions remained within a specific distance of the mean center of pressure, known as the base of stability. Within these excursions, the mean center of pressure remained close to the overall mean throughout the activities they tested. Thus, the postural center of pressure is the relatively stable region where postural stability can be maintained (Murray, et al., 1975); this is the central tendency of postural sway. In some studies, unstable surfaces have been combined with a force plate to investigate postural stability in the company of postural perturbations. Some researchers have placed the force plate on top of the unstable surface (Gouwanda, Gopalai, Lim, & Lim, 2014) while others have opted to place the unstable surface atop the force plate (Chiou, Bhattacharya, Lai, & Sucoop, 1998; Strang, et al., 2011).

3. Postural Sway Summary

Postural sway is the process of finding and maintaining the ideal reference position for an upright stance. High frequency, low amplitude movements provide a feedback process around low frequency, high amplitude central tendencies of sway. Sensory inputs

such as visual stimuli and haptic touch stimuli provide cues that support the maintenance of upright stance evidenced through changes in postural sway. Given this body of research, if changes to sway variability occur when lanyards are worn while completing a task, they may provide a useful correlate to the effect of lanyards on postural stability and task performance in a moving environment. Differences in postural sway are often measured using force plates. A validated force plate was used as a measurement device in the current thesis.

E. CONTRIBUTORS TO POSTURAL STABILITY AND TASK PERFORMANCE

Task performance and postural sway are not enough by themselves to explain the changes in human performance in a moving environment. Factors such as learning, fatigue, and individual differences have an impact on how each individual copes with motion while completing a task. Including analysis of these factors in postural stability studies is critical to gaining better understanding of performance parameters, and informing tradeoff discussions in systems design.

1. Learning

There is substantial evidence that learning occurs during task performance in a moving environment. Task-specific learning effects in a motion condition appear to reduce the MII rate while performing that task (Crossland & Rich, 1998). Improved task performance may also provide evidence of adaptation to motion over time (Malone, 1977). There is support in the literature for both specific and generalized adaptation to motion. Tuning of postural sway to motion conditions as previously discussed is one field of study that may indicate that learning to maintain upright posture in a moving environment has occurred (Goldfield, et al., 1993; Ooteghem, et al., 2008). Research has also shown that postural control mechanisms (stance width, spatial magnitude of postural sway and magnitude of postural sway when looking at near versus far visual cues) change in the first few days of exposure to sea motion (Stoffregen, Chen, Varlet, Alcantara, & Bardy, 2013; Varlet, et al., 2015), supporting a learning hypothesis. In the case of the proposed USCG/NASA study participants, novices may still be developing postural stability in both

specific motion profiles and specific task performance. More experienced participants however, may have learned how to tune their postural sway to various motion profiles and demonstrate sufficient adaptation to both diverse motion conditions and the specific postural stability demands of the task. In the present study, differences in sway variability and time to complete the task may indicate a learning effect.

2. Fatigue

Fatigue is a complex topic with many definitions and causes. Webster's dictionary defines fatigue as "weariness, exhaustion from labor, exertion or stress" (Merriam-Webster, 2017). Two contributors to fatigue were expected to occur in the USCG/NASA: motion-induced fatigue (MIF) and muscular fatigue. MIF (fatigue related to exposure to motion) has been shown to increase over time while underway due the exertion needed to counter the motion to maintain postural stability (Colwell, 1989; Grech, Elischer, & McLean, 2008; Miller, Smith, & McCauley, 1998). It has also been shown to change in parallel with the severity of motion conditions (Grech, et al., 2008). Some studies have shown that short term exposure (3 hours or less) to motion does not affect physical task performance (Shattuck, Shattuck, Smith, & Matsangas, 2013). Longer term studies conducted at sea address fatigue in their analyses, but very few attempt to separate MIF from other types of fatigue such as sleep-related fatigue and exercise-induced muscular fatigue.

In their text on Occupational Biomechanics, Chaffin, Anderson and Martin (2006) describe muscular fatigue as a "reduction in the ability to exert force in response to voluntary effort." This may be reflected as a reduction of total force applied by the muscles, a change in perception of the difficulty of work, or a reduction in motivation to apply force. Repetitive activation of muscle fibers, even low intensity intermittent activations will fatigue metabolic systems that support muscle activation. This type of activation of muscle fibers is likely to occur on balance training devices such as a BOSU balance trainer. An additional source of fatigue may be the specific task. Tasks that involve overhead reach are known to be more fatiguing than those that do not require overhead reach (Chaffin,

Anderson, & Martin, 2006, pp. 25, 234–235; Dickerson, Meszaros, Cudlip, Chopp-Hurley, & Langenderfer, 2015).

A validated measurement of subjective fatigue is the CR10 Borg Rating of Perceived Exertion (RPE) Scale (Borg & Borg, 2001; Borg & Kaiser, 2006; Perceived Exertion, 2015). This level-anchored ratio scale provides anchors of a subjective measure (in this case, fatigue) by attaching familiar meaning to specific levels (such as feeling somewhat fatigued after a moderate exercise session). The scale allows individuals to rate their personal perception of feeling using a right skewed distribution. Individuals are more likely to be familiar with various magnitudes of fatigue below moderate fatigue, and less familiar with high levels of fatigue, thus more granularity is required below a moderate fatigue level. At higher levels, there is less granularity, and at the highest level, there is room to exceed the highest possible level of fatigue as that degree may not be known. An initial estimate of extreme fatigue may soon be supplanted by even higher fatigue levels. This method of assessing fatigue has been shown to be valid with less subjective levels of fatigue, such as heart rate and blood lactates (Borg & Kaiser, 2006).

3. Personnel Characteristics

The dimensions and physical characteristics of the human body have an effect on the human ability to perform under motion (Crossland, et al., 2007; Hue, et al., 2007). Body mass index (BMI), a biometric calculated by dividing body weight in kg by squared height in meters (Body Mass Index [BMI], 2015) is the only information regarding body dimensions collected by the USCG (United States Coast Guard, 2015). There is mixed evidence that BMI has been associated with postural stability. Hue et al. (2007) found that over 50% of the variability in postural stability was accounted for by BMI in a morbidly obese population. Southard, Dave and Douris (2010) found no differences between two different BMI groups in ability to maintain center of gravity over a base of support. The difference between these two studies is the BMI range they studied: Hue et al. studied a group of men with a mean BMI of 35 (> 30 is classified as obese), whereas Southard, et al. studied individuals with a BMI ranging from 25 to 29.99 (classified as overweight by the

CDC). The latter study is closer in range to the USCG population which limits BMI to 27.5 (Body Mass Index (BMI), 2015; United States Coast Guard, 2015).

While BMI is an easy-to-use estimate for body comparisons, it is not as precise as center of gravity, which is affected by changes in weight and dynamic alterations to body position (Swearingen, 1962), and is the predominant measurement in human performance in motion research (Crossland, et al., 2007; Graham, 1990). More recent studies have noted that humans make adjustments in body position to maintain postural stability which also alters the bodily center of gravity (Duncan, et al., 2013; Matsangas & McCauley, 2013). When compared to postural stability, Greve, Alonso, Bordini and Camanho (2007) found a relationship between BMI and postural stability; in subsequent research they found that center of mass demonstrated a stronger effect than BMI (Greve, Cug, Dulgeroglu, Brech, & Alonso, 2013). The height component of BMI may be more important than weight in a population that excludes the obese. Evidence for this is derived from the earliest model for MII prediction, Graham's tipping coefficient (Graham, 1990). Height of the COM was the denominator and half the stance width was the numerator in that early estimate of susceptibility to MIIs. Height of COM can be adjusted, but it is related to physical height in an immutable way. Height, weight and stance width were collected in the present study.

4. Contributors Summary

Learning effects are evident in task performance and adaptation to motion. Adaptation to motion may be shown through improved task performance, or changes to postural sway. In the present study, learning effects were expected in the form of reduced sway variability, particularly in the unstable surface motion conditions. Task performance was expected to increase as participants adapted to the motion and learned strategies for task completion. In an effect opposite to learning, subjective fatigue was expected to increase as the experimental trials advanced. Increased fatigue could manifest in increased sway variability and decreased task performance over the course of the experiment. Distinctions between MIF and muscular fatigue were not studied. BMI, height and weight are known to be contributors to postural stability. All three characteristics were explored

in this study to determine if any individual characteristic (height and weight) or the combined value (BMI) influenced the results.

F. HYPOTHESES

The hypotheses for this study are presented here.

1. The variability of postural sway will be lower when lanyards are connected to the body than when they are not.
2. The central tendency of postural sway will be deflected opposite the force of lanyards when the lanyard connections are unevenly distributed.
3. Time to complete a simulated task will be less when lanyards are connected.

The following factors were considered.

1. Due to learning effects, sway variability will decrease with increasing task order in the initial trials of the unstable surface configurations.
2. Due to learning effects, time to complete will decrease over the trials in all configurations.
3. Fatigue will increase with increasing task order in all configurations.
4. Due to fatigue, task performance and sway variability will increase in the later trials.
5. Height, weight and age will contribute to models for sway variability and time to complete the task.

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III. METHODS

A. OVERVIEW

A controlled laboratory experiment was conducted to assess postural sway variability and human performance on a stable and unstable platform in varying lanyard configurations. A structure was built to support a hook assembly that allowed a rudimentary simulation of the mechanical task performed by the BCM on the OTH. The task was completed on a stable surface and an unstable surface under three different lanyard configurations. Six combinations of lanyard and surface were possible. Each combination was assigned a number 1 – 6, and a six by six Latin square was constructed. Each row of the square became the trial order for one participant. A participant completed five of each combination for a total of thirty total trials per participant. The resulting six experimental trial orders, and the participants that conducted each one, are shown in Table 2.

Table 2. Quasi random experimental design

Participant	Trial order - 5 replications in each set					
	First set	Second set	Third set	Fourth set	Fifth set	Sixth set
1,7,13,19,25,31	AP/BOSU	UC/BOSU	A3P/BOSU	A3P/Block	UC/Block	AP/Block
2,8,14,20,26,32	A3P/BOSU	AP/Block	AP/BOSU	UC/BOSU	A3P/Block	UC/Block
3,9,15,21,27,33	UC/BOSU	AP/BOSU	AP/Block	UC/Block	A3P/BOSU	A3P/Block
4,10,16,22,28,34	AP/Block	UC/Block	A3P/Block	A3P/BOSU	AP/BOSU	UC/BOSU
5,11,17,23,29,35	A3P/Block	A3P/BOSU	UC/Block	AP/Block	UC/BOSU	AP/BOSU
6,12,18,24,30,36	UC/Block	A3P/Block	UC/BOSU	AP/BOSU	AP/Block	A3P/BOSU

Participants completed a demographics and fitness questionnaire prior to conducting the study and answered questions regarding the study after the experiment. The study took approximately one hour to complete per participant.

B. PARTICIPANTS

This section discusses the selection and demographics of the study participants.

1. Selection

The Naval Postgraduate School Institutional Review Board reviewed and approved the human subject research protocol for this experiment. All participants read and signed a consent form prior to beginning the study. Participants were NPS civilians and students, recruited by email and flyer distribution. Participants were excluded from participating in the study based upon the following criteria:

- medical problems that might cause trouble keeping balance, dizziness, or vertigo
- sinus, ear or balance related problems such as sinus infection or ear infection
- surgery on a joint or bone in the last six months
- in physical therapy for a joint or bone surgery or other condition
- experiencing pain in any joints (foot, ankle knee, hip, etc.) or muscles that cause supportive assistance for balance, such as holding on to hand rails to traverse up or down stairs
- reliance on a brace or other supportive device on a joint or bone for daily activities
- pregnancy
- other similar condition that may impact natural balance and ability to adjust balance without assistance

2. Demographics

It total, 36 healthy participants (26 males, 10 females), with an average age of 36 years (range 23–55) took part in the study. Average height was 69 inches and weight was 181 pounds (ranges were 59 to 77 and 117 to 245 respectively). Thirty-one participants were active duty military. All but one participant actively engaged in physical activity.

Balance related physical activity included: yoga (23), martial arts (12), and Pilates (8). Eleven participants had participated in a small boat crew, and six had extensive experience conducting the operational evolution in question on the USCG/NASA study. Experience using a BOSU balance trainer ranged from none (16), to once or twice (11) to extensive BOSU experience (9). One BMI outlier was identified: The self-reported height and weight indicated a BMI in the obese range; however, subjective observation contradicted that conclusion.

C. MATERIALS AND METHODS

The apparatus, surface configurations, lanyard configurations, questionnaires and measurement devices are discussed in this section.

1. Apparatus

An 89.5 inch by 90 inch by 102 inch wooden structure was constructed to simulate the NASA ICAB (Figure 5). A HYET ET1218 electric hoist with 440 pound lifting capacity was attached to the rear floor support beam, with a system of two pulleys that supported the cable vertically up the rear support beam, to the center top beam of the frame across to four inches short of the front support. The front support pulley allowed a hook with six pound weight to lower in front of the participant, 28 inches away from the center of the standing position. The weight was constructed of four athletic wrist and ankle weights secured around the hook housing with duct tape. A U-bolt was attached 19 inches above the floor and four inches into the lateral space of the frame. Four lanyards were connected to the structure in similar locations to the ICAB (adjusted eight inches upward to account for the height of the Block/BOSU): the left and right lateral posterior lanyards were connected at a height of 74 inches on the left and right supports, the center posterior lanyard was connected 88 inches in height on the center rear support, and the front lanyard was connected 16 inches in height on the center front support.



Figure 5. Apparatus, shown with Block configuration

2. Block configuration

A two-foot square piece of plywood was placed 34 inches back from the center vertical beam and centered laterally within the structure. The plywood served as a support for the block or force plate during testing. The position of the plywood was marked on the floor to ensure it did not move over the course of the experiment. The stable experimental surface was the block configuration: an eight inch high wooden block was placed within marked boundaries on the plywood, and a force plate was placed on top of the block within marked boundaries (Figure 6). All three surfaces were centered laterally in line with the front and rear support beams; the block and force plate were centered fore and aft with respect to the plywood. The block height was selected to match the visual references to a participant standing on the BOSU balance trainer, but was slightly lower to account for a loss of height in the BOSU when a human stood on it.

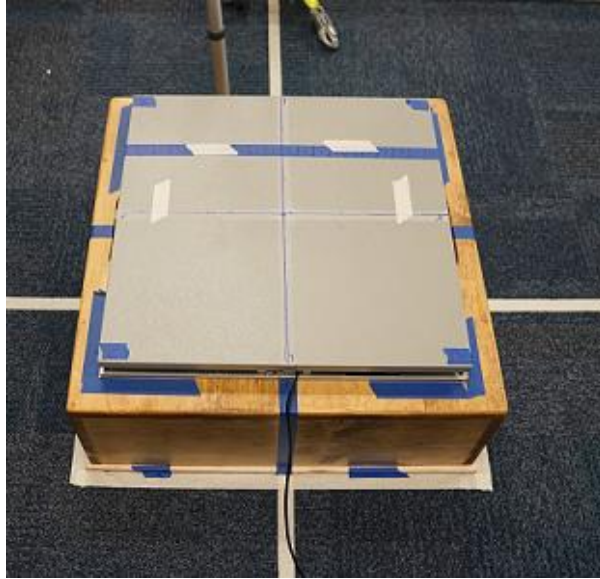


Figure 6. Standing surface Block configuration with white tape indicating foot position

3. BOSU Configuration

For the unstable surface trials, the force plate was placed directly on the plywood within centered, marked boundaries. A BOSU balance trainer (BOSU Balance Trainer, 2018) inflated to nine inches was placed on top of the force plate (Figure 7), and centered by tape marks that referenced the center of the BOSU and aligned with tape marking the center of the force plate and extending outwards toward the boundaries of the apparatus. The tape marks allowed the BOSU balance trainer to be placed in the same position for each trial. The BOSU was situated on top of the force plate in order to keep both unknown values (human and BOSU) on one side of the measurement device. Additionally, the difficulty of keeping the force plate centered on the BOSU during repeated trials, and possibility of the force plate slipping off the BOSU during a trial were deemed undesirable. However, in this arrangement, the unstable surface had an unknown attenuation effect on the postural sway measures. As a result, direct comparisons between the stable and unstable conditions were not possible.

A conventional medical walker was provided for balance support when transitioning on and off the BOSU.

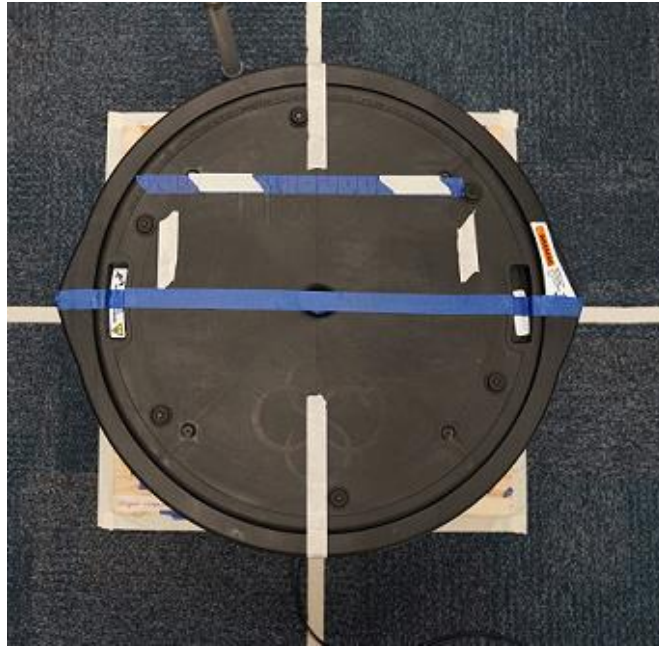


Figure 7. BOSU balance trainer centered on force plate and plywood

4. Lanyards and Personal Protective Gear

Participants wore a USCG helmet and fall protection harness with front and aft D-rings for all trials. Self-retracting inertia lock lanyards identical to those proposed for the USCG/NASA experiment were attached to the lanyard connecting points (Figure 8), either in an anterior and posterior pair (AP condition), a single anterior and triple posterior group (A3P condition) or no lanyards (unconstrained or UC condition). The center rear lanyard was the shortest at four and one half feet long, and the only lanyard that could run out of length within the confines of the apparatus. The length of this lanyard in the configuration proposed for the USCG/NASA study had similar characteristics. The anterior side lanyards were six feet long and the center lanyard was 10 feet long. Each lanyard imparted approximately 1.8 pounds of force in the static condition, and over two pounds of force when the lanyard was extended. The movement force was dependent on accelerations. At high accelerations, the inertia mechanism would lock, stopping movement on the lanyard. No participant moved quickly enough to lock the inertia mechanism of a lanyard.

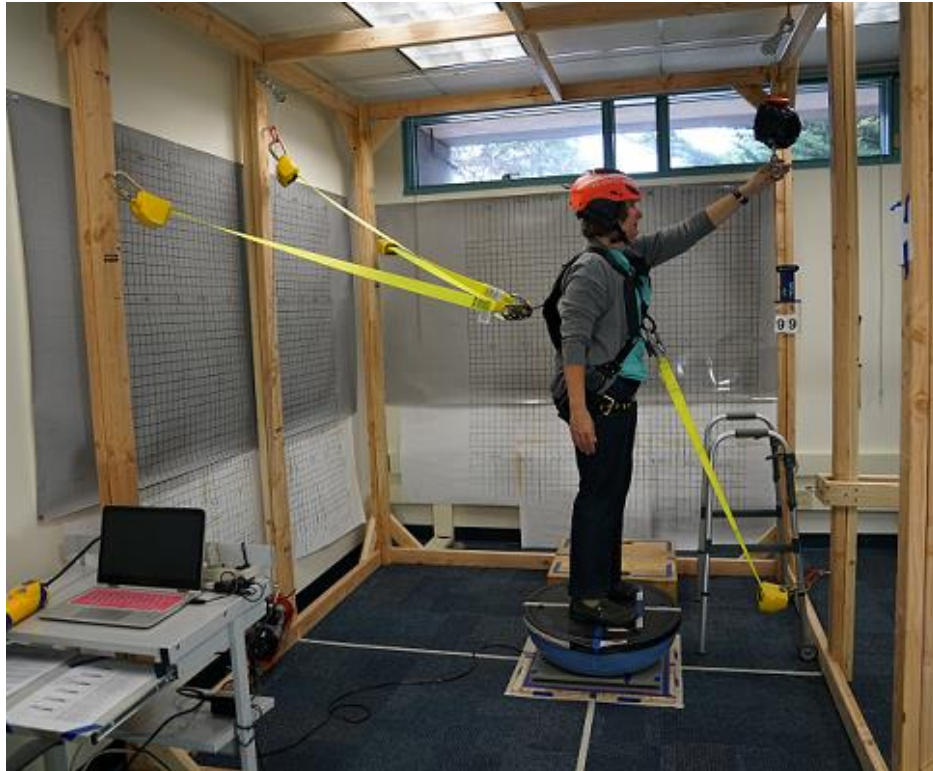


Figure 8. Researcher demonstrates reaching for the hook with harness and A3P lanyard configuration

5. Questionnaires

Participants completed a pre-trial questionnaire, which included basic demographics, questions regarding balance-related physical activities, and service mandated physical fitness tests (Appendix A). A Borg CR10 rating of perceived exertion scale was used to assess fatigue prior to the start of the experiment, after a training trial, and after each ten trials for a total of five fatigue ratings (Appendix B). A table that displayed the CR10 rating levels was posted on the vertical beam to the right of the participant for reference during the experimental fatigue ratings. A BORG fatigue level of six was determined as the maximum allowable level of fatigue. No participant reached that level of fatigue in this study. At the conclusion of the study, participants answered several questions regarding their perceptions about the task (Appendix C).

6. Video

Video cameras were centered on the sagittal and coronal plane of the plywood. The position of the cameras was marked on the floor at each tripod leg to ensure the camera stayed aligned during data collection (Figure 9). A grid pattern representing one inch increments at the plywood center was drawn on the walls opposite the video cameras (Figure 10). Standard definition video was collected on both axes for all trials using Sony HDR UX20 digital HD video camera recorders. Video analysis was conducted using Adobe After Effects CC version 15.11 build 12, on a Dell D03X computer with Intel core i7 processor 3.30 Ghz processing speed and 16 GB Ram.



Figure 9. Anterior video camera placement (left) and side camera placement with alignment tape (right)



Figure 10. Wall grid

7. Force Plate

An AMTI Accugait force plate (Golriz, et al., 2012) was used to measure changes in center of pressure. AMTI Balance Clinic Software version 2.03.00 was used to collect and process COP data on a Dell Latitude 5480 laptop with Intel i5 processor, 4GB Ram and Windows 10, 64 bit operating system. The force plate was connected to a USB port on the laptop via a Tripp Lite high speed USB serial adaptor. The force plate used a Cartesian system with 0,0 in the center, positive y to the anterior and positive x to the right. The data acquisition rate was set to 50 Hz, and units of measurement were set to inches. COP data was recorded for 1,158 trials. Seventy-two trials were baseline trials and six trials were excluded that contained duplicated information due to researcher error leaving a sample size of 1,080. The software produced raw data output files for each participant and output files that averaged the force plate readings by trial. All reported results used the average data for each trial, rather than the full raw data set.

D. PROCEDURES

When participants arrived at the lab, they read and signed a consent form and then the demographics and fitness questionnaire. The study procedures were described and explained in detail. Next, the participants put on the harness and helmet. Participants were instructed to tighten the harness enough to be snug but not uncomfortable.

The next step was to establish the experimental stance on the block. The participant was asked to step onto the block with the force plate atop the block (Block configuration). Participants were instructed to assume what felt like a natural and secure stance width, centering his or her stance laterally and longitudinally on the force plate. If the participant's foot arch was not over the centerline of the force plate, the researcher encouraged the participant to reposition the feet in the anterior/posterior direction to a more centered position. The researcher then marked the participant foot position at the widest part of the ball of the foot on the sides, and at the forward most protrusion of the shoes near the big toe. This was done to ensure the participant positioned his or her feet in the same position for each trial (Figure 11). The researcher read an explanation of the CR10 scale and asked the participant to provide a baseline fatigue rating. Once the foot position was marked and a baseline fatigue rating obtained, the participant was asked to stand quietly while 30 seconds of COP data were collected.

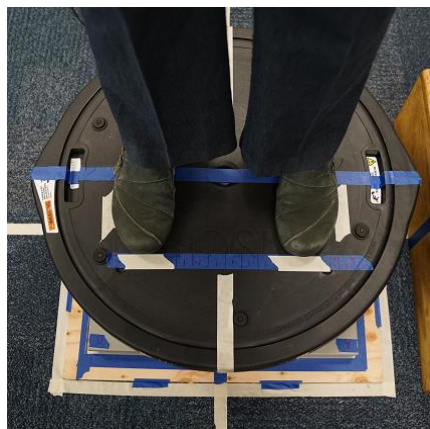


Figure 11. Feet marking with tape in BOSU configuration

Next, participants stepped off the block and the researcher changed the Block configuration to the BOSU configuration. The researcher then demonstrated how to safely get on the BOSU, find a comfortable stance width, and to get off the BOSU using the walker for support. Participants were allowed to get on the BOSU ball and adjust the stance width for as long as necessary to find a comfortable position. Foot position was then marked in the same manner as the block. Once the feet were marked, participants were allowed an additional 20 seconds to get used to standing on the unstable surface. Participants were then asked to stand quietly on the BOSU and a baseline BOSU COP measurement was taken.

Following the BOSU baseline, participants were asked to step off the BOSU and the Block configuration was restored. The researcher described the task (Appendix C) and allowed the participants to practice the task. Participants were not given specific instructions on how to position their bodies to complete the task, or how to best manipulate the hook. They were allowed to develop strategies to complete the task at their own discretion. At the conclusion of the practice, participants were allowed to ask any questions, and then asked to provide a fatigue rating. This concluded the pre-study phase; participants were ready to start the main data collection.

Each participant performed 30 total trials in total, grouped in six sets. Each set was comprised of five trials in a single surface and lanyard configuration pair. A single trial commenced when the participant was positioned on the platform with the appropriate lanyard configuration. After the participant indicated he or she was ready to begin, the researcher initiated force plate data collection, and then commenced lowering the hook using a remote switch on the hoist. The researcher would continue lowering the hook until it was level with the U-bolt and could be connected. The trial concluded when the hook was connected to the U-bolt. Between consecutive sets of BOSU trials, the BOSU was checked for deviation from the centered position. After each set of ten trials, a CR10 fatigue rating was obtained. After the completing data collection, participants answered questions on the post-trial questionnaire (Appendix D), and the researcher answered any participant questions regarding the study.

E. VARIABLES

The study independent and dependent variables are discussed in this section.

1. Independent Variables

Two independent variables were platform configuration (Block or BOSU) and lanyard configuration (UC, AP or A3P).

2. Dependent Variables

The main dependent variables in this study are variability of sway, central tendency of sway, and a task performance metric of time to complete the task. Contributing factors and behavioral data are also discussed here.

a. Variability in Postural Sway

“Area 95” was the area of an ellipse that encompasses 95% of the COP data points for each trial. This metric was provided by the Balance Clinic software. The Area 95 variable was used to assess sway variability for each trial.

b. Central tendency in Postural Sway

The Balance Clinic software calculated the average displacement in the y-axis from the platform center for each trial. To adjust for individual stance differences in the sagittal plane, the y average values from the baseline trials were subtracted from the y average values for the experimental trials by platform type (i.e. Block baseline y average was subtracted from y average values for all Block trials). The resultant value was “y avg delta” which was used to assess the central tendency of postural sway.

c. Task Performance

The time to complete (TTC) was derived from video data. TTC was calculated by selecting the frame (seconds and frame at a 29.97 fps video rate) when the hook began to move to the time the audible sound of the hook connecting was recorded. The TTC value was converted to a continuous value to the hundredths place (8.23 for example). TTC was not obtained for 59 trials due to video failures; this included no data at all for one

participant, and no Block data for another. TTC was not recorded for the 30-second baseline trials. The number of missing TTC data points is shown in Figure 12.

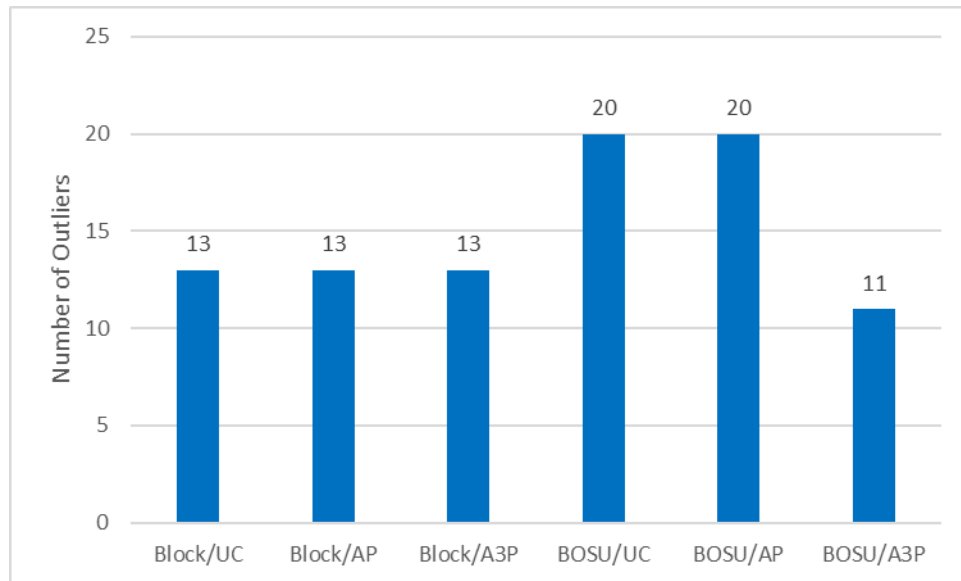


Figure 12. Distribution of TTC missing data

d. Contributing Factors

The following exploratory variables were investigated as potential confounds to the main dependent variables: task order, fatigue ratings, height, weight, age, boat crew experience and fitness experience. Learning was assessed by exploring differences in the dependent variables by task order. Fatigue was assessed using the BORG CR10 ratings and comparing those ratings to task order results. Personnel characteristics were explored by including them in model development to identify important predictors. Observed behaviors were qualitatively identified through video analysis. The demographic exploratory variables were not counterbalanced, so no inferences could be drawn from the corresponding results. They were only investigated as indicators of confounds to the results.

e. Behavioral Data

Video data was analyzed to identify participant behaviors that may have had an impact on the dependent variables. The video analysis was supplemented with researcher notes taken during the experiment regarding participant actions or comments pertaining to task performance or trial condition.

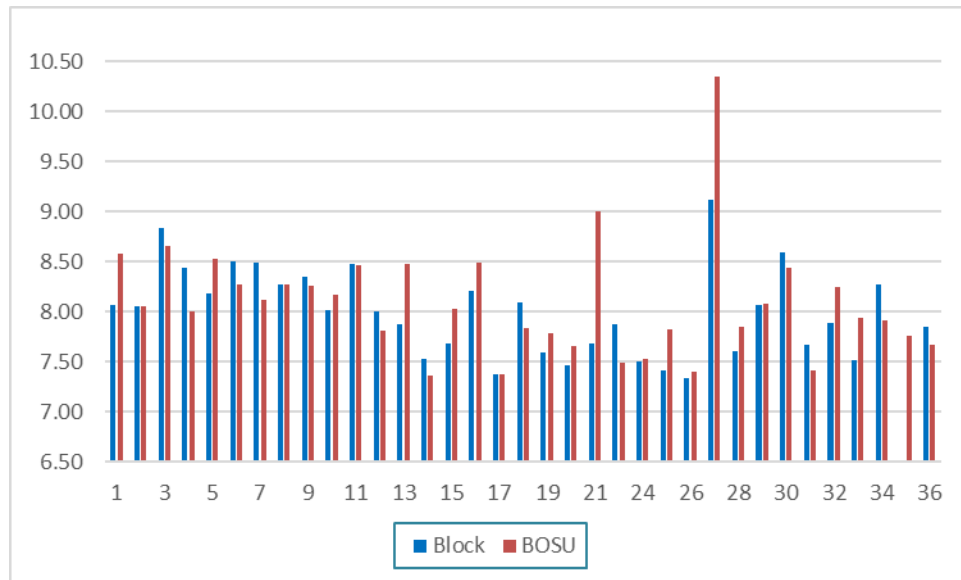
IV. RESULTS

A. OVERVIEW

Statistical analyses were conducted using JMP Pro version 13.1.0 and IBM SPSS Statistics version 25 (Freidman's tests). Significance levels were set to 0.05 for all hypothesis tests. All comparisons were conducted within platform conditions and not between, due to the fundamental differences between the Block and BOSU characteristics.

Assumptions for mixed effects linear models were checked using the usual residual diagnostic procedures. Area 95 residuals were not normally distributed and showed increasing variability with fitted values, so a logarithmic transformation was applied to stabilize the variance of the independent variable and satisfy the linear model mixed effects assumptions. Y avg delta residuals met normality and equal variance conditions. Hypothesis one (area 95) and two (y avg delta) were assessed using a mixed effects model, with participant number as a random effect to account for the dependent nature of individual differences. Three outliers were excluded from the Area 95 and y avg delta analyses due to high leverage COP values. The high COP values in all three outliers were due to high x maximums attributable to a lower extremity ML oscillation that developed between the participant and BOSU. This oscillation had no relationship to the lanyard configuration.

Hypothesis three (TTC) residuals did not display equal variance and attempts at transformation were unsuccessful. Figure 13 shows the individual differences in time to complete, which were the likely source of the unequal variance. Differences in task performance strategies, stance choice and natural balance between participants resulted in a few participants taking consistently longer to complete the task. For example, participant number 27 had considerably longer time to complete. This may be due to an inconsistent hook connection (task completion) strategy, which caused delays that were compounded when motion was introduced.



Participant 23 had no TTC data; participant 35 had no Block TTC data

Figure 13. Average TTC by participant and platform configuration

In order to facilitate a non-parametric Friedman's test, an average TTC for each BOSU and lanyard configuration by participant was calculated. Friedman's test was conducted on the average TTC values blocking on participant.

Fatigue was evaluated separately from the main dependent variables due to different measurement frequencies (every tenth trial instead of every trial). Friedman's test was used due to a violation of the normality assumption. Fatigue trends were compared to task order trends using Wilcoxon signed rank test in order to determine if fatigue was a likely contributor to differences in the dependent variables. Personnel characteristics were analyzed using post-hoc model development to determine if height, weight, BMI or age were contributors to the models. Finally, post-hoc video analysis was conducted at the participant level (not trial by trial) to make an initial assessment of human interaction with the platform condition, the lanyard condition and the task.

In order to understand the differences between observed variability on the BOSU balance trainer and the Block configuration, some observed statistics are shown in Table 3. This table is intended to give the reader an understanding of the variability of COP data observed on the two surfaces. It should be emphasized that the COP recorded from the

BOSU when an individual is standing on it is fundamentally different than the COP recorded when the individual is standing on the force plate. Postural sway was visibly more variable on the BOSU than the Block to a larger degree than is indicated by Table 3. It was thought that the BOSU attenuated postural sway, but the degree and nature of the attenuation could not be quantified.

Table 3. Baseline variability information

	Average y axis variability of COP (in)	Average x axis variability of COP (in)	Area in inches (SD) of 95% ellipse
Block	0.20	0.07	0.31 (0.60)
BOSU	0.40	0.31	2.41 (1.12)

B. ASSESSMENT OF THE EFFECT OF LANYARDS

This section includes the main findings for variability of sway, central tendency of sway and time to complete. Exploratory analysis of contributors to postural stability such as learning, fatigue, and personnel characteristics are also discussed.

1. Main Findings

Statistically significant differences were found between some configurations in variability in postural sway and central tendency, but not in time to complete the task.

a. Variability in Postural Sway

The mixed effects model included task order and lanyard configuration as fixed effects and participant as a random effect. The models were statistically significant in both the Block ($F(2, 470) = 5.12, p = .006$) and BOSU ($F(2, 473) = 20.41, p < .001$) configurations (where F is the F-statistic with degrees of freedom in parentheses and p represents the p value throughout). In the Block configuration, the AP/Block condition was approaching significance as a predictor of Area 95 ($t = 1.77, p = .077$). In the BOSU

configuration, the A3P lanyard configuration was a statistically significant predictor of Area 95, $t = 5.98$, $p < .001$. Figure 14 shows the Area 95 results.

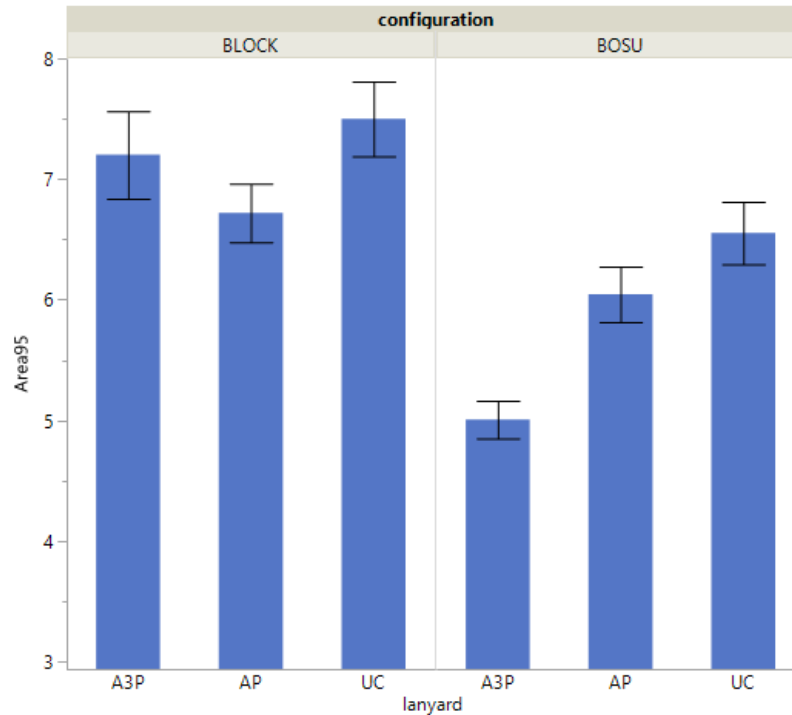


Figure 14. Area 95 (in inches) by configuration and lanyard. Vertical lines denote the Standard Error of the Mean.

b. Central Tendency in Postural Sway

The fixed effects of the mixed effects model using task order and lanyard configuration as fixed effect were statistically significant in both the Block and BOSU configurations. Lanyard was a statistically significant predictor in both models (Block, $F(2, 470) = 131.36$, $p < .001$; BOSU, $F(2, 474) = 77.45$, $p < .001$). This analysis revealed that the A3P condition was significantly different from the UC condition on both the Block ($t = 14.87$, $p < .001$) and the BOSU ($t = 11.36$, $p < .001$). In both cases, the estimate of A3P y avg delta was less than the UC y avg delta estimates, indicating that the lanyards altered central tendency to the posterior direction (Figure 15).

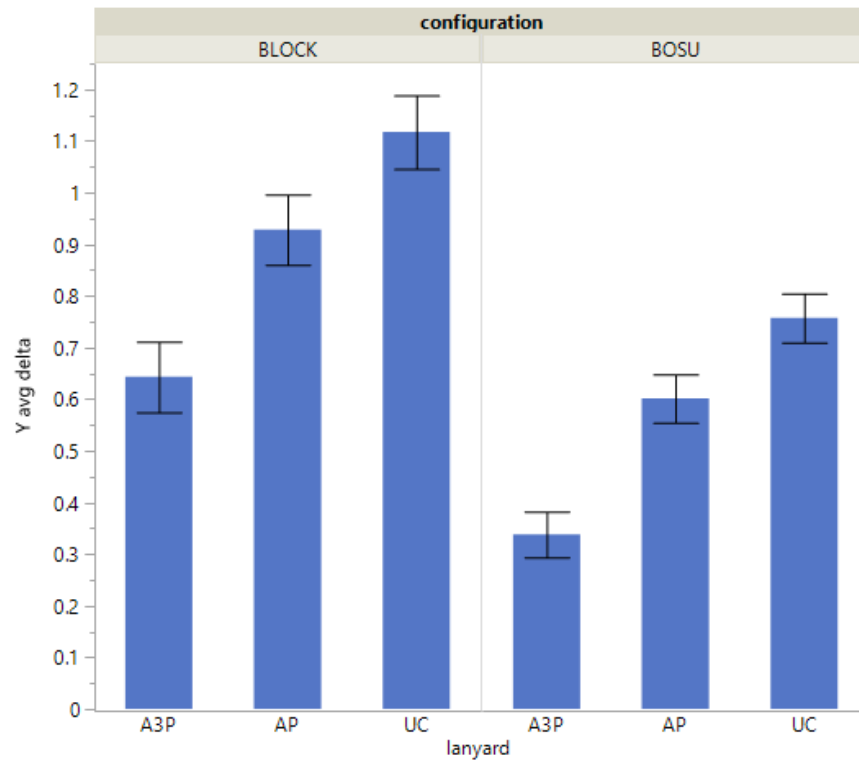


Figure 15. Means with standard error bars for y avg delta variable (in inches) showing central tendency

c. Task Performance

No statistically significant differences in TTC were identified in either the Block ($\chi^2(2, N = 36) = 3.86, p = .145$) or BOSU groups, ($\chi^2(2, N = 34) = 1.18, p = .552$) (where χ^2 is the chi-square test statistic for homogeneity with degrees of freedom and sample size N given in parentheses). Average values for TTC by configuration and lanyards are shown in Figure 16.

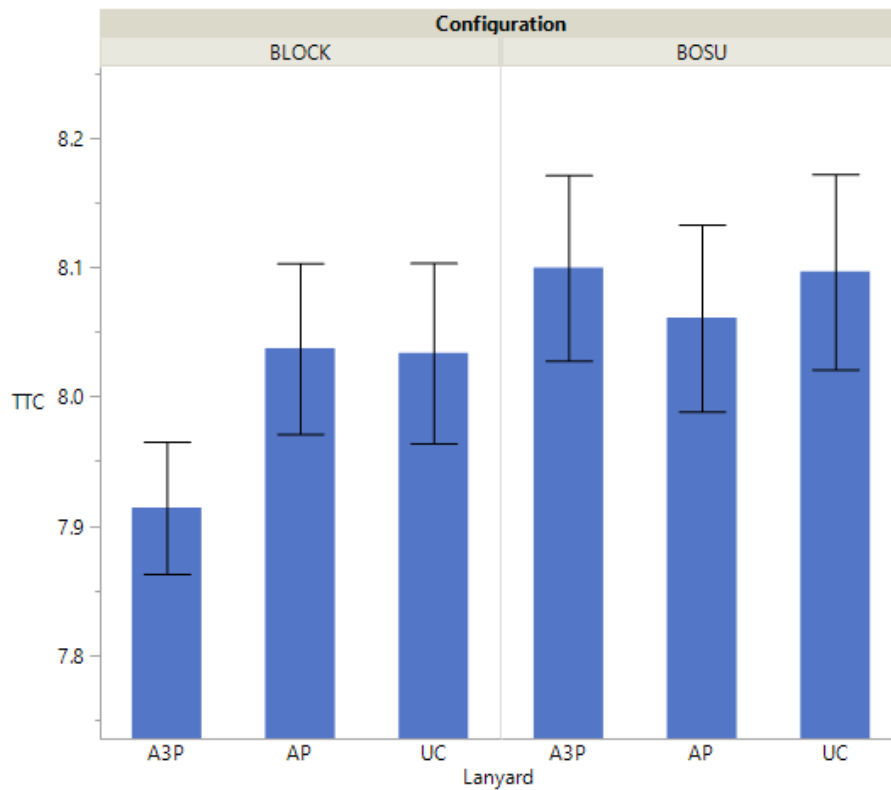


Figure 16. Time to complete trends with standard error bars

C. EXPLORATORY ANALYSIS

This section will explore learning effects using task order as the dependent metric. Fatigue will be assessed through a non-parametric Friedman's test, and trends compared to time to complete data. Personnel characteristics such as height, weight and age are associated with postural stability, as discussed in Chapter II. These characteristics were added to the statistical models to determine if they confounded the results already reported.

1. Learning

Learning effects were assessed by including task order in the mixed effects model analyses. COP data was considered by platform configuration, as learning to maintain balance and complete the task on a stable platform would not be the same as learning on an unstable platform. Task order was a statistically significant predictor in the BOSU configuration Area 95 model, $F(30, 468) = 1.69$, $p = .013$, but the effect size was small,

and no patterns could be discerned. Task order was not a statistically significant predictor to y avg delta in any platform and lanyard configuration. A mixed effects model was used to determine task order effects on time to complete, and both platform configurations were considered together. This is because learning how to complete the task was expected to weigh more heavily on task completion times than postural stability, although both may be important. The TTC model was statistically significant, with task order (not lanyard) as a significant predictor, $F(31,921) = 2.59, p < .001$. This result was limited to a reduced time to complete between the first and second trial, ($t = 2.21, p = .027$). When platform configurations were considered separately, the differences between the first and second trial remained in the Block condition, with additional differences at trials 11, 19 and 20; in the BOSU condition, the second trial became non-significant and trial eight became statistically significant. The randomness of the significant trials in the TTC/task order comparison contradicts the pattern we would expect to see if a learning effect were present.

2. Fatigue

Fatigue ratings were assessed at five intervals during the experiment: before the baseline COP readings (“baseline”), after training (“training”), and three successive trial intervals (“trial 10,” “trial 20” and “trial 30”). Similar to TTC, fatigue ratings were not normally distributed. Differences between fatigue ratings were statistically significant, $\chi^2(4, N = 32) = 78.42, p < .001$. A Wilcoxon signed rank analysis was conducted to determine which fatigue ratings were different at a statistically significant level. All fatigue ratings were significantly higher than the baseline fatigue ratings. The t test statistics and p values for subjective fatigue ratings between all assessments are reported in Table 4. Fatigue ratings increased over the course of the trials, as shown in Figure 17, however this was not a consistent finding for all individuals as shown in Figure 18.

Table 4. Test statistics for subjective fatigue ratings between all assessments

	Training	Baseline	Trial 10	Trial 20
Baseline	$t = 1.99, p = .004$			
Trial 10	$t = 4.57, p < .001$	$t = 4.94, p < .001$		
Trial 20	$t = 5.49, p < .001$	$t = 5.79, p < .001$	$t = 2.83, p < .001$	
Trial 30	$t = 4.88, p < .001$	$t = 5.10, p < .001$	$t = 3.56, p < .001$	$t = 1.96, p = .010$

Although fatigue was investigated as a confounding variable to the main dependent variables, the frequency of fatigue reporting prevented linking fatigue ratings with specific trials. If fatigue were a statistically significant predictor of the dependent variables, it would manifest as increased sway variability or decreased performance (longer TTC) as the task and motion exposure increased. The main findings did not suggest increased sway or decreased performance with increased task order, so fatigue was not suspected to be a significant factor to the results of this study.

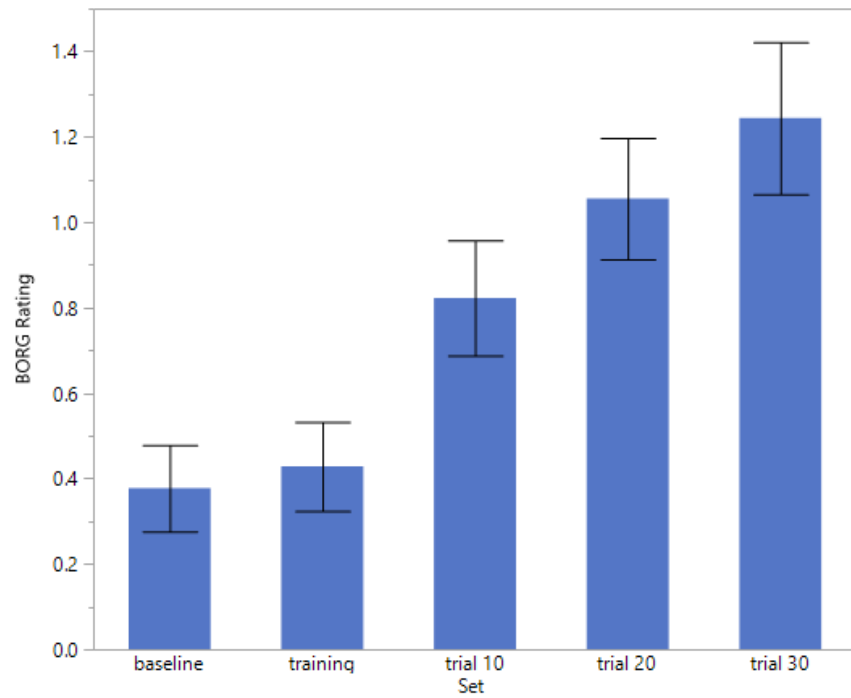
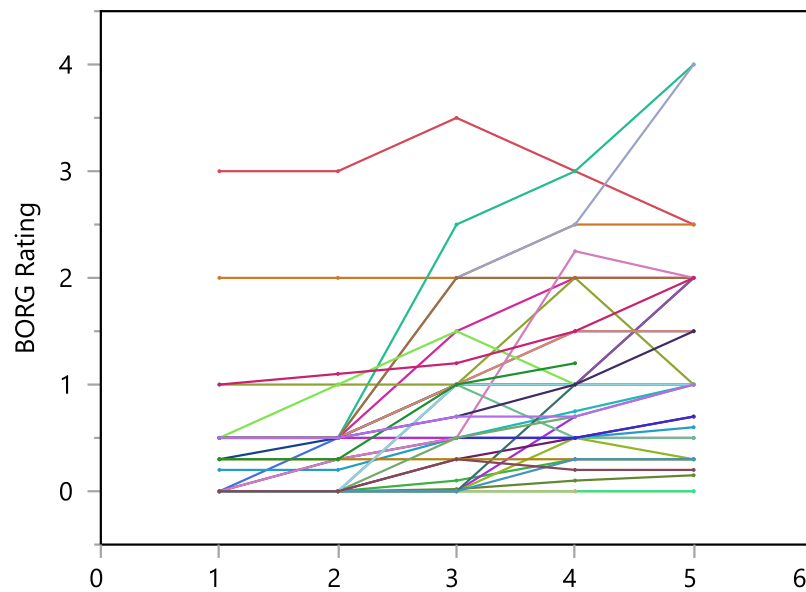


Figure 17. Average fatigue levels with standard errors



Set is on the x axis, where 1 is the baseline rating, 2 is the training rating, 3 is after trial 10, 4 after trial 20 and 5 after the last trial.

Figure 18. Fatigue ratings by participant as a function of order of given fatigue rating

3. Personnel Characteristics

Next, height, weight, BMI and age were investigated for associations with the three main dependent variables. This analysis was purely exploratory; no inference can be drawn due to the lack of appropriate counterbalancing for these factors. When age and BMI were added to the mixed effects model in the BOSU condition, age was found to be associated with decreased variability in postural sway ($F(1,32) = 5.74, p = .022$), and BMI was found to be associated with increased variability, $F(1,32) = 5.70, p = .023$. These effects may not be very important however, as the estimates for these effects were very small (parameter estimates ≤ 0.01). Furthermore, a decreased variability in sway for older individuals is contrary to a vast body of research (see (Murray, Seireg, & Sepic, 1975)). One explanation for the difference found in this study might be the level of physical activity reported by the participants. All participants regardless of age reported some physical activity. This may have contributed to the mitigation of postural stability decay in the older adults in this study. Finally, the connection between BMI and lanyard configuration may be explained by performance differences noted in both the shorter and taller participants.

In hypothesis two (y avg delta) when age and BMI were added to the model, some effects similar to those reported in hypothesis one were found. In the Block condition, age was associated with a more anterior central tendency in the AP configuration ($t = 3.26, p = .001$), but not in any other configuration. BMI was not statistically significant. In the BOSU configuration, age ($F(1,32) = 5.14, p = .030$) and BMI ($F(1,32) = 5.43, p = .026$) were statistically significant. In older adults, the estimate of A3P/BOSU central tendency was anterior by 0.007 inches ($t = 2.56, p = .010$), but the AP/BOSU configuration was not different from the UC/BOSU condition ($t = 0.09, p = 0.92$). For BMI, the estimate of AP/BOSU configuration central tendency was anterior to the UC/BOSU ($t = 3.2, p = .001$) but the A3P/BOSU was to the posterior, and not statistically significant. Height and weight contributed to the model, but appeared with the expected relationships as covariates of BMI. Although there are some interesting findings which may be important directions for future research, no patterns from personnel characteristics were observed that would change our interpretation of the main findings reported in this chapter.

4. Behavioral Observations

Preliminary video analysis yielded a number of interesting observations regarding participants' behavior during the data collection. These observations include identification of participants whose physical dimensions and postural strategy led to full extension of the shortest center rear lanyard. The resulting restriction on movement had important implications for the USCG/NASA study.

5. Postural Strategy

Video analysis revealed differing postural strategies among participants. The most obvious differences in postural strategies involved the angle of the knee. This determinant was unique between participants, and was more pronounced than the waist or ankle angle (although all three are inter-related). Four broad groups are shown in Figure 19: obtuse knee angles of 160 degrees or greater (nearly upright, four participants), approximately 135 degrees (16 participants), approximately 90 degrees (10 participants), and less than 30 degrees (a deep squat, three participants). Two participants varied their strategy based on whether the configuration was Block or BOSU.



Clockwise from top left: 30 degrees, 90 degrees, 160 degrees and 135 degrees. Yellow lines on the knee and thigh show the angle that was considered.

Figure 19. Postural strategies used during the task

a. The Problem of the Center Rear Lanyard

The center rear lanyard was the shortest of the four. Seven participants in this study reached the end of the lanyard identifiable by fixed tension during the process of completing the task. Repeated interactions with the center rear lanyard were clustered in the group with a lower postural strategy (90 or 30 degrees), but participants with a more upright strategy were not exempt. Interaction with the center rear lanyard almost always resulted in a change in a participant's approach to completing the task. Three participants reported leaning on the center rear lanyard. Another participant reported leaning on the center rear lanyard and tipping forward, losing his balance as he returned to an upright stance and pressure from the center rear lanyard released.

6. Subjective Assessments

Twenty-nine (80%) participants reported an awareness of the lanyards while conducting the task. Eighteen felt that the lanyards helped their stability and task performance; twelve reported that the lanyards hurt their performance (some reported both). Five participants reported that the lanyards were a distraction from the task, and five felt they had no impact on the task or balance. Of those who felt that lanyards interfered with balance, none reported leaning back. All three felt they leaned forward to compensate for the extra force, contrary to the research findings.

D. SUMMARY

The variability of postural sway on the BOSU Balance trainer was lower when participants had four lanyards connected to the body in an uneven distribution (three in the posterior and one in the anterior). Four lanyards also predicted a central tendency of postural sway that was further aft than an unconstrained posture in both the Block and BOSU configurations. There were no statistically significant differences in time to complete the task. Learning effects were observed between the first and second trial, but not thereafter. Fatigue increased over the course of the study, but did not appear to be related to changes in task performance or postural stability.

Video analysis of participant behavior when performing the task revealed postural strategies that may indicate two or more groups with different stability parameters based on degree of knee bend. Further analysis is planned to determine if blocking by postural strategy would provide a more robust understanding of the results. Likewise further analysis is needed regarding interactions with the center rear lanyard at full length, which had observable effects on postural control and strategies.

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V. DISCUSSION

A. OVERVIEW

Statistically significant and non-significant results are discussed in this chapter. Important trends will also be discussed. Figure 20 shows the results for the main hypotheses together, and will be the main figure used for the discussion.

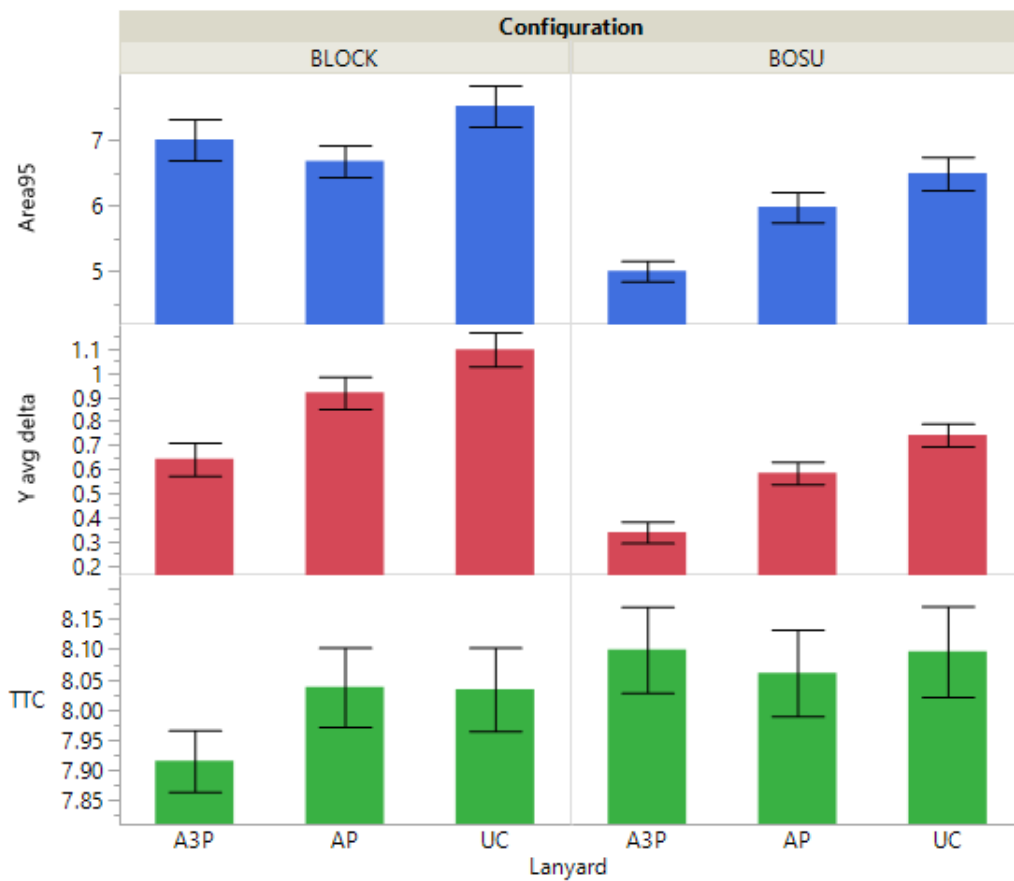


Figure 20. Graph plotting averages of the three dependent variables by configuration with standard error bars.

B. SWAY VARIABILITY (HYPOTHESIS ONE)

This section reviews the results for sway variability and explains the relevance to the USCG/NASA study.

1. Results Review

As assessed by the area of the 95% ellipse, postural variability in an unstable environment (i.e., the BOSU configuration) is lowest when four lanyards are attached to the body, increases when two lanyards are attached, and is highest when no lanyards are attached to the body. Figure 20 shows there was a clear trend of increasing sway as the number of lanyards attached to the body decreased in the BOSU configuration. These findings are consistent with postural stability research on the influence of force cues on postural sway (Jeka, 1997; Maurer, et al., 2006). We postulate that our findings can be explained if we consider the forces and the additional sensory input the self-retracted lanyards impart on the body. This trend does not exist in the stable environment (i.e., the Block condition). This may be explained by the idea that adults have such a finely tuned postural sway feedback system on a stable surface that variability is already at a minimum, and postural control muscles have sufficient strength in the normal range to counter a light force applied by the lanyards.

The hypothesis that the variability of postural sway would be lower when lanyards are connected to the body than when they were not was partially supported. Statistical tests rejected the null hypothesis in both the Block and BOSU configurations; only the A3P BOSU configuration was found to be a statistically significant predictor of reduced sway variability. The implications of this finding for the USCG/NASA study are important to retain experimental validity. They also contribute to the body of research on postural stability.

2. Relevance to NASA Study

The results show that lanyards change a fundamental characteristic of postural sway, reducing the variance of sway as the number of lanyards attached to the body increase. In high amplitude motion simulation, the reduction in postural sway induced by

the lanyards may assist participants in finding a postural reference position in high sea state simulations, leading to fewer MIIs than would be experienced without lanyards. This artificially enhanced performance may lead to more generous estimations of human performance limitations than exist in the operational environment. Overestimation of human capabilities in the USCG/NASA experiment will have direct effects on future systems selection, and may put future BCM lives at risk.

C. SWAY CENTRAL TENDENCY (HYPOTHESIS TWO)

This section reviews the results for sway central tendency and explains the relevance to the USCG/NASA study.

1. Results Review

Contrary to the hypothesis, the central tendency of postural sway was directed toward the force of lanyards when the lanyard connections are unevenly distributed on the body. Furthermore, evenly distributed lanyard force also altered central tendency of postural sway toward the anterior of the body, although the effect size was not large enough to be statistically significant. Similar trends were found in both the stable and unstable surface conditions.

The results of this study are counter to the findings of Maurer et al. (2006), whose investigation of pull forces are most like the self-retracting lanyards used in this study. Their study forces applied to the body using force-controlled cable wenchers, and their participants were asked to maintain an upright body position with their eyes closed. The pull force varied based on the position of a sinusoidal motion perturbation of the standing surface. A counter-lean may have been detected in their study because the primary goal was maintenance of an upright body position; it may also be because the force applied varied with the motion. Even though they included mental math to preclude attentional focus on upright stance, periodic attention on the goal may have led to a conscious counter-lean. In the present study, the goal was task completion, with no instruction given on maintaining upright stance. The intensity of applied force was comparable to some of the forces applied by Maurer et al. (2006) (six to eight Newtons); however, the lanyard force in the present study was nearly constant. The diversion of attention to task completion in

the present study may have led to a reduced compensation for the unequal force, and an offset of central tendency in the direction of the uneven applied force.

It is less clear in previous research why equal force on the body would result in an aft-direction central tendency. One possible explanation may be related to differences in postural sway and body axes. Postural sway in the AP direction (Chen & Stoffregen, 2012) with reduced variability due to equal forces applied to the body may look like an aft displacement central tendency, due to the forward direction of joint mobility in the body.

2. Relevance to USCG/NASA Study

Changes to the direction of central tendency of postural stability introduces confounds to the USCG/NASA experiment, where trained and experienced BCMs are the population of interest. These participants will be both adapted and habituated to the motion profiles that are modeled in the simulation. Alterations to their postural central tendency may have a deleterious effect on their postural control in otherwise familiar motion conditions. The result may be artificially poor performance in initial trials and a lag in task performance for the duration of the experiment as they adapt to a different central tendency. Contrary to lanyard-induced changes to sway variability, central tendency changes may lead to an underestimation of human capabilities. Underestimates of human capabilities in the USCG/NASA study would lead to a reduction in operational effectiveness of future USCG systems.

D. TIME TO COMPLETE (HYPOTHESIS THREE)

This section reviews the results for time to complete and explains the relevance to the USCG/NASA study.

1. Results Review

No significant differences were found in the time to complete the task in any configuration. Figure 20 shows that only the A3P Block condition had a lower average time to complete than the other configurations. This trend was somewhat surprising given that the Block condition is a stable platform and the task was relatively simple. Trial order may have had an impact, as two of the six participants who completed the Block A3P

condition first were missing TTC data from that configuration. As a result, increased TTC due to learning in the first three to five trials for those two participants would not be accounted for. The trend revealed in the Block A3P configuration is suspect due to the missing data.

Task performance data in a moving environment are stubbornly complex; this is clear from the literature. Fatigue (Grech, et al., 2008; Shattuck, et al., 2013) and learning (Crossland & Rich, 2000; Goldfield, et al., 1993; Ooteghem, et al., 2008) affect task performance in subtle ways. More conscious processes such as human skill (Baitis, et al., 1984) and propensity to work harder to accomplish a task in more difficult conditions (Malone, 1977) also affect task performance. This inherent complexity means that task performance by itself is not a reliable measurement of human performance in a moving environment. Consideration of the multitude of task performance confounds, by either by measurement or by control, is a necessity in this type of research.

2. Relevance to USCG/NASA Research

The task in this study was relatively simple, so the low variability in time to complete the task is not surprising. If the only hypothesis were task performance, differences in postural stability would be hidden. The USCG/NASA study has a more complex task with much greater motion perturbations; therefore, differences in task completion time are expected. However, it is important to analyze other aspects of postural performance such as MIIs and individual balance strategies to provide a more nuanced understanding of human performance during the study. In addition, TTC is an important variable to interpret learning and fatigue effects.

E. LIMITATIONS

In this study, specific instructions for posture during the task (squat or stand) and how to complete the task (e.g., how to hold the hook) were not given. This was a deliberate choice to mimic the USCG/NASA study where participants will be allowed to choose their postural and task completion strategies. The disadvantage to this approach is that individual differences that are not the primary focus of study (e.g., problem solving) create confounds to task performance metrics. This can also be reflected in MII research. For example,

Crossland et al. (2007) allowed participants to adjust stance width during varying motion conditions and found higher stability in higher motion conditions in two out of three studied tasks. Other researchers such as Matsangas and McCauley (2013) did not find an increase in stability (represented by fewer MIIs) at higher motion profiles when stances were fixed throughout motion conditions. In order to develop a clearer picture of stability, it may be advisable in future research to provide specific task completion instructions while allowing a choice of stance width. Another approach would be to compare differences between fixed stance and choice stance groups in order to study of the effect of postural strategy on task performance metrics.

The placement of the force plate sensor under the BOSU was a conscious choice for this study. Placing the force plate on top of the BOSU would have been a more direct measurement of COP data and allowed comparisons between platform configurations but would have required complex mathematical transformations. This configuration would also add to the practical complexity of getting on and off the BOSU and preventing movement of the force plate between trials. It would also increase instability as the BOSU surface tipped away from horizontal due to the weight of the force plate and the low coefficient of friction between force plate and BOSU surface. The configuration chosen for this experiment prevented comparisons between Block and BOSU configuration and permitted attenuation of postural variability through the BOSU.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Our results show that there are differences in postural sway variability and central tendency between unconstrained and lanyard configurations. Lanyards reduced variability and altered the central tendency of postural sway. Learning effects were limited to the first and second trials, and although subjective fatigue increased throughout the trials, it did not significantly affect the task performance results. Personnel characteristics such as age, height and weight showed small effects, but there was no clear indication that these characteristics were important to the results of the study. Other factors such as postural and task completion strategy may have had an effect on the results. Further analysis of these variables is warranted.

B. RECOMMENDATIONS

Based on our findings, we propose the following recommendations for the USCG/NASA study. The recommendations are presented in increasing order of bias introduced by the lanyards and the risk to external validity.

- If safety permits, it is recommended to perform the experiment without lanyard restraints.
- The four lanyard configuration with self-retracting lanyards is not recommended.
- Extend the center rear lanyard to a length that eliminates the possibility of leaning.

C. DIRECTIONS FOR FUTURE RESEARCH

Further exploration is planned for the video data collected in this study. For example, postural strategies noted in the behavioral observation section will be examined for relationships to the main hypotheses of this study and implications for MIIs. Total body lean for each trial will be tabulated and analyzed by configuration using the wall grids to

deepen the understanding of the observed differences in central tendency of postural sway. Body segment movements will be analyzed to see if any differences emerge between participants or in individual trials that can help understand the present study or the USCG/NASA experiment.

Future studies may provide information on the value of forces applied to the torso that could stabilize posture in high risk tasks such as USCG small boat recovery. Perhaps an innovative system solution exists that can transform stabilization provided by lanyards from experimental confound to a system affordance. The lanyard would extend the combined human/system sea state limitation by meeting human limitations with innovative system design. Such a system represents the promise of HSI-focused research: improved total systems performance achieved through a bold exploration of complex research questions with applied operational goals.

APPENDIX A. QUESTIONNAIRE

Pre-experimental questionnaire for Evaluation of Safety Protocols

You are invited to participate in a research study entitled "Evaluation of Safety Protocols for NASA AMES/USCG Small Boat Recovery Experiment." This project will determine if there are differences in postural stability while completing a simple task wearing different safety equipment configurations. This questionnaire asks for some basic information that will help us interpret the results of the study.

1. Are you active duty military?
2. What is your gender?
 - a) Female
 - b) Male
 - c) Other
3. What is your age?
4. What is your height in inches?
5. What is your weight in pounds?
6. Does your branch of service require a fitness test?
1. If your branch of service requires pushups, please enter the time requirement for pushups and how many you were able to complete on the most recent fitness test you completed.
 - a) time limit:
 - b) number of pushups:
2. If your branch of service requires situps, please enter the time requirement for situps and how many you were able to complete on the most recent fitness test you completed.
 - a) time limit:
 - b) number of pushups:
3. If your branch of service requires a run, please enter the distance required and the time you were able to complete the run on the most recent fitness test you completed.
 - a) distance:
 - b) time:
4. If your branch of service requires a swim, please enter the distance required and the time you were able to complete the run on the most recent fitness test you completed.
 - a) distance:
 - b) time:

5. If your branch of service requires other fitness measures, please list the measure and your performance on the most recent fitness test you completed here:
6. Have you ever tried yoga?
 - a) Please describe your yoga experience, in frequency and length of time. (For example, you might say I practiced yoga weekly, for two years starting in 2011):
 - b) Do you still practice yoga regularly?
7. Have you ever tried Pilates?
 - a) Please describe your Pilates experience, in frequency and length of time. (For example, you might say I practiced Pilates weekly, for two years starting in 2011):
 - b) Do you still practice Pilates regularly?
8. Have you ever tried any kind of martial arts?
 - a) Please describe your martial arts experience, in frequency and length of time. (For example, you might say I practiced Jiu Jitsu and karate weekly, for two years starting in 2011):
 - b) Do you still practice martial arts regularly?
9. Have you ever been part of a boat crew that conducted side launch and recovery operations alongside a ship?
 - a) When you were a part of the boat crew, were you ever the crewmember who connected a hook from the crane on the ship to the small boat?
 - b) How often, and for how long, did you serve in that position on the small boat (for example, you might say my small boat crew launched daily on a 6 month deployment, I did two deployments in 2007–2008):
10. Please enter your participant number here. If you do not know your participant number, please ask the researcher.

Thank you for completing this questionnaire. Please notify a researcher that you have completed the questionnaire and you are ready to begin the experiment.

APPENDIX B. BORG CR10 FATIGUE RATING SCALE

Several times during the experiment, we will ask you to rate your perception of fatigue. We will ask this after your task practice, in between each series of lanyard and block configurations , and at the end of the experiment. Your rating should reflect how tired you feel, mentally and physically. Do not concern yourself with any one factor such as fatigue in one part of your body, but try to focus on your total feeling of fatigue. Look at the rating scale below. This is the scale we will ask you to use when rating your fatigue. It ranges from 0 to 10, where 0 means “not fatigued at all” and 10 means “maximally fatigued.” Choose the number that best describes your level of fatigue at the time. It is possible that you may feel your fatigue is at a 10 (maximally fatigued), only to find that the next time you give your rating you feel even more fatigued. That is why there is an 11 on the sale. As an example, when you get up in the morning after a very long and satisfying rest, you might say you are 0, “not fatigued at all,” whereas after a moderate exercise session, you might say you are 4, between “somewhat fatigued” and “fatigued.” Don’t worry about memorizing the scale, this will be available to you during the experiment. Try to appraise your feeling of fatigue as honestly as possible, without thinking about the experiment or the things you have done. Your own feeling of fatigue or tiredness is important, not how it compares to other people. Listen to the expressions and then give your response.

0	Not fatigued at all	
0.3		
0.5	Extremely light fatigue	Just noticeable
0.7		
1	Very light fatigue	
1.5		
2	Light fatigue	
2.5		
3	Moderate fatigue	
4		
5	Strong fatigue	
6		
7	Very strong fatigue	
8		
9		
10	Extremely strong fatigue	strongest
11		
	Absolute maximum fatigue	

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APPENDIX C. TASK INSTRUCTIONS

“You will now have an opportunity to practice the task we will be asking you to do. I will ask you if you are ready, you should respond with a “ready” or “yes” when you are ready. When the task begins, the hook you see over your head will begin to lower. As soon as you can reach it, reach up to grasp the hook. Do not wait until the hook is close, reach up as soon as you can reach it with your hands. As the hook lowers, do not attempt to pull the hook down, only guide it as it lowers. When the hook is within range of the connecting point, please connect the hook to the connecting point. When you have the hook connected, please announce, “hooked.” At this time the task is complete. We will disconnect the hook, raise the apparatus the next task will begin. We will ask you to do this task in several configurations: without lanyards, with one lanyard connected to your chest and one to your back, and with one connected to your chest and three to your back. You will do this task in all three of those configurations on both the block and the BOSU ball. You are about to have an opportunity to practice the task, but before we do that do you have any questions about the task?

(Answer questions)

Conduct trial sequence

After practice trial sequence is complete:

When you do this with the lanyards on, they may lock in place. If that happens, we’ll try to finish the task. Please tell me when if a lanyard has locked so I can make a note of it, and we can reset the trial if the position you are stuck in does not allow you to complete the task. Please also tell me if you accidentally find yourself leaning on the hook, or anything else unusual in a particular trial.

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APPENDIX D. POST-TRIAL QUESTIONNAIRE

Post-trial questionnaire

1. What was easiest about completing the task?
2. What was the hardest thing?
3. What was different between the three variations?
4. Did the lanyards change how you moved your body to complete the task?
5. If so, please explain how.

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