Simulated motion negatively affects motor task but not neuromuscular performance

by

© Gregory Pearcey

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Abstract

The objectives of this thesis were 1) to describe how motor task and neuromuscular performance is affected by various types of environmental perturbations and 2) to examine the effects of simulated motion on motor task and neuromuscular performance, conduct an experiment to examine the effects of one hour of simulated ship motion on motor task and neuromuscular performance. Sixteen males participated in two one-hour experimental testing conditions; 1) motion and 2) control. Motor task performance was measured through a simple reaction time and computerized visuomotor accuracy tracking task, while neuromuscular performance was measured through maximal voluntary contractions, voluntary activation, evoked muscle contractile properties and biceps brachii electromyography of the elbow flexors. Results indicated that motor task but not neuromuscular performance was affected by simulated motion due to ongoing sensorimotor adaptation that results in an overload of cognitive resources.

Dedication

I would like to dedicate this thesis to my deceased mother, Kerry Lorraine (Butt) Pearcey.

Her unconditional love and kindness has molded me to become the person I am today.

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The support that I have received during my education at Memorial University has been paramount. First and foremost, I would not have considered pursuing a Master's Degree if it weren't for the encouragement I have received from my supervisor and mentor, Dr. Duane Button. His supreme guidance and support have allowed me to excel in a way that I had never thought was imaginable. I began to work with Dr. Button in the final year of my undergraduate degree, and have had the privilege to continue work with him ever since. He has been the best teacher, colleague and friend a student could ever desire. His mentorship and support has been crucial for my academic and personal development. He deserves the utmost respect for what he has done for me, and for that reason, I thank him.

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"When we meet real tragedy in life, we can react in two ways–either by losing hope and falling into self-destructive habits, or by using the challenge to find our inner strength."

— *Dalai Lama*

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List of Symbols, Nomenclature or Abbreviations

CO	Control condition
dof	Degrees of freedom
EMG	Electromyography
ES	Effect Size
ITT	Interpolated Twitch Technique
MIF	Motion Induced Fatigue
MII	Motion Induced Interruption
MO	Motion condition
MVC	Maximal Voluntary Contraction
rms	Root mean square
RT	Reaction Time
SMS	Ship Motion Simulator
VAT	Visuomotor Accuracy Tracking
$\dot{V}O_2$	Volume of Oxygen Consumption
WBV	Whole Body Vibration

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Chapter 1: Review of Literature

1.1: Introduction

Employment in the offshore oil sector exposes workers to extended shift work, moving environments and physically demanding work. These demands are expected to increase as exploration and production moves toward the mid-Arctic. While at sea, seafarers perform a lot of physical and mental work for extended periods of time, and often the movement from the ship can cause fatigue, a phenomenon referred to as motion-induced fatigue (MIF) (Wertheim 1998). It has been suggested that MIF may negatively affect an individual's ability to complete a task, thus putting their safety at risk. Unfortunately, research investigating the prolonged effects of MIF on human performance is limited. There has been research performed to investigate motion-induced changes in human performance under acute simulated motion (1-25 minutes of exposure to motion) environments. Cycling (Wertheim et al. 2002) and walking (Heus et al. 1998) in simulated motion environments have resulted in decreased peak $V0_2$ and increased energy expenditure, respectively. It has also been shown that there are decrements in cognitive, perceptual and complex task performance (Wertheim 1997). To date, there is no previous work that has examined prolonged effects of simulated motion exposure on reaction time, tracking tasks and voluntary force production. Since short duration (< 20 minutes) motion results in decrements in the performance of various tasks (Wertheim et al. 1997b), and increased motion is hypothesized to create MIF (Wertheim 1998), it is likely that exposure to longer duration (> 1 hour) motions will have a negative impact on an individual's task performance. Thus, the purpose of this review was to: 1) describe considerations when examining simulated motion, 2) illustrate how human performance of various tasks is affected by various types of simulated motions, and 3) provide a detailed review of various measurements of motor task performance.

1.2: Simulated Ship Motion

Many simulated ship motions are modeled after those measured aboard vessels at sea. In a review of ship motion environments affecting human performance, Pingree (1988) suggested that the motions of the majority of ships are low frequency angular motions and that these motions are predominantly heave, pitch and roll at frequencies lower than 1Hz. Thus, simulated ship deck motion is commonly created using motion profiles, which are comprised of a series of equations that produce various amplitude and frequency sine waves. The motions are comprised of 6 degrees of freedom; heave, surge, sway, pitch, roll, and yaw, which blend together to simulate motions felt while at sea. Due to variations in weather and ship sizes, motions experienced at sea can vary. Thus, it is difficult to choose an appropriate simulated motion to represent motion that would be experienced on a daily basis by offshore workers. Previous studies have examined; changes in metabolic rates (Heus, Wertheim et al. 1998; Wertheim, Kemper et al. 2002; Marais 2010), muscle recruitment patterns during lifting tasks (Matthews et al. 2007), muscle activation and maximal voluntary forces (Grover 2012), lifting task capabilities (Holmes et al. 2008), and cognitive and perceptual task performance (Wertheim 1997), during simulated motion of various motion profiles and durations. The duration of motion exposure in these studies ranged from 2 minutes (Holmes, MacKinnon et al. 2008) to 45 minutes (Wertheim 1997). To date, no study has examined the prolonged effect of motion on fatigue and task performance, nor the recovery time course of these tasks following the cessation of motion.

The intensity of the simulated motions that affects task performance is another important factor to consider. Marais et al. (2010) examined the difference in metabolic rates during two different intensity motion profiles and observed increased resting metabolic rates from rest to both a high intensity and low intensity (half the acceleration of the high intensity) simulated motion conditions. They noted that the higher intensity motion resulted in a greater increase in metabolic rate, however, it is possible that a low intensity motion may induce decrements in human performance although higher motion conditions would likely elicit greater physical, and perhaps, cognitive impairment.

1.2.1: Methodological Considerations When in Motion

1.2.1.1: Motion Experience

A participant’s experience of functioning within a motion rich environment may play a role in how they interact and respond during simulated motion under experimental conditions. If a participant has considerable experience as a seafarer, it is likely that they will respond differently than an individual who has never been aboard a vessel at sea. For example, in most studies (Heus, Wertheim et al. 1998; Wertheim, Kemper et al. 2002; Bos et al. 2005; Matthews, MacKinnon et al. 2007; Holmes, MacKinnon et al. 2008; Newell et al. 2008; Lin et al. 2010) participants were volunteers of the university student population that likely have experienced very little ship motion simulation or time at sea aboard a vessel. These participants, who are naive to motion, likely experience greater effects of motion on metabolic workloads (Heus, Wertheim et al. 1998; Wertheim, Kemper et al. 2002; Marais 2010), lifting task ability (Holmes, MacKinnon et al. 2008), and cognitive, perceptual and complex task performance (Wertheim 1997) than experienced individuals would. It is likely that due to their extensive experience at sea, the participants recruited by Wertheim et al. (2002) may have been less affected by motion at sea. Thus, it seems that motion experience has a marked effect on task performance decrements experienced under motion states.

1.2.1.2: Motion Sickness

By definition, motion sickness is any sickness that is induced by motion (Bos, MacKinnon et al. 2005). The predominant cause of motion sickness is stimulation of the organs of balance in the inner ear (Bos, MacKinnon et al. 2005). It is also suggested that vision has a significant effect on the amount of motion sickness experienced by individuals in a simulated motion environment. Bos et al. (2005) compared the subjective sickness experienced by 24 individuals in three different conditions; 1) blindfolded, 2) vision inside of the simulator only, and 3) vision outside of the simulator, and found that the highest levels of sickness were observed when an individual could only see within the simulator. They also examined if a person was concentrating on a point of interest (i.e. computer monitor) in motion (on the motion simulator) or not in motion (off of the motion simulator) and found that, if the point of interest was in motion, there were lower levels of motion sickness. Various studies have also determined that motion sickness is affected by the duration of exposure to motion (Wertheim 1998). The longer a person is in motion, the more likely they will experience motion sickness. Of the studies reviewed, several had participants drop out due to motion sickness while some did not. To reduce motion sickness and, therefore, reduce subject drop out in a study, the object which a participant's visual focus is aimed should be in motion with the participant. Since there is an experiential component that can predict motion sickness, participants can also be screened for motion sickness susceptibility (Kennedy et al. 1992).

1.2.2: Direct Results of Perturbations in Motion

Norrish et al. (1990) performed a national survey on the nature and prevalence of injuries among New Zealand's fishermen, and found that the major contributor was the poor working conditions, one of which being the effects of the sea causing various motions on the vessels. The effects of ship motion induce both motion-induced interruptions (MII) and MIF, both of which can be detrimental to human performance.

1.2.2.1: Motion-induced Interruptions

Often times, the motions of a ship perturb an individual and cause them to lose balance or slip, thus interrupting the task that they are performing. This is a concept known as a MII, and was first introduced by Applebee et al. (1980). Graham (1990), created a MII model to predict the frequency and intensity of motion that would cause a MII to occur (i.e. when a person's center of mass would displace outside of the base of support). Provocative ship motions have been shown to cause a high musculo-skeletal load as well as motor challenges, thereby increasing workload (Torner et al. 1994). Torner et al. (1994) found increased co-activation at most joints, resulting in over stabilization of the joints as a result of induced MIIs during simulated motion. Duncan et al. (2010) examined the balance and stability of people in simulated ship motions and discovered that there are major decreases in balance and stability while in motion. In fact, there is a need for changes in corrective strategies to support the balance of an individual in motion. Increases in spinal twisting during manual materials handling have been found in motion environments, indicating that there is a higher risk for injury and fatigue (Kingma et al. 2003). Holmes et al. (2008) showed increases in lateral bending and twisting, along with increased erector spinae activation during lifting in motion environments, which could result in an increased risk for over exertion injuries. Duncan et al. (2012) found that there were decreased lifting velocities during lifting tasks, and suggested that when in motion, people are more cautious with their movements. However, it is possible that the motions may actually reduce an individual's ability to perform a lifting task at a high velocity due to the stabilization required to maintain balance and caution may not be a factor. Coincidentally, evidence for postural prioritization also exists in motion. This means that if a perturbation to posture is present, there will be decrements in reaction time (RT) in order to prioritize balance (Redfern et al. 2002). It is likely that a combination of the abovementioned outcomes of MIIs would result in neuromuscular fatigue that could also contribute to MIF.

1.2.2.2: Motion-induced Fatigue

Wertheim (1998) refers to motion-induced fatigue (MIF) as fatigue that is the result of a biodynamics problem, or what has been called "weariness after exertion," rather than the result of either loss of quality of sleep or motion sickness. In a review of naval biodynamics problems, Colwell (1989) suggested that MIF was an important source of performance degradation and contributed to a higher incidence of mistakes in the naval community. Perhaps the main contributor to fatigue at sea, is weariness that people experience after they exert themselves in motion which has been described to be distinct from neuromuscular fatigue (see section 3 for more detail). This is supported by results found by Baitis et al. (1995) during their MII study in which they reported that the measured levels of energy expenditure (muscle fatigue) were relatively small compared to the participants' capacity to perform work. With regards to human energy expenditure, Wertheim et al. (1997a) found that peak oxygen consumption ($\dot{V}O_{2\,Peak}$), as a measure of physical workload, might indeed be lower in a moving rather than a stationary environment. In a later study (Wertheim, Kemper et al. 2002), they found that the $\dot{V}O_{2\,Peak}$ results from a graded exercise test were also significantly lower during motion conditions. Since performing a given task in motion results in higher $\dot{V}O_2$ and that $\dot{V}O_{2\,Peak}$ is decreased, humans are working at a higher percentage of their peak $\dot{V}O_{2\,Peak}$ during a given task in motion compared to performance in a stable environment.

The combination of increased metabolic workload and MII, result in more effort to maintain body posture and carry out motor tasks in motion because of neuromuscular fatigue of the postural muscles. This decrement in motor task performance could be further complicated by a loss of sleep, heavy workloads and the debilitating effects of motion sickness (Wertheim 1998), thus potentially leading to even more decrements in motor task performance.

1.2.2.3: Measures of Human Performance in Motion

Typically, a person's ability to safely complete a task, and thus, perform work, is based on their ability to remain error-free. Some fundamental components of performing common tasks while at work include: 1) reaction time, 2) coordination, 3) voluntary force production, 4) baseline cardio-respiratory fitness, and 5) balance. A combination of these components, among others, will help dictate whether a person will perform a task in an error-free manner.

Seafarers perform considerable amounts of work, similar to those workers on land, but are exposed to inconsistent and constant oscillatory platform motions. In a controlled environment, these motions have been shown to induce acute decrements in various types of task performance and work capacity of individuals and it is hypothesized that increased exposure to motion causes increased drowsiness and decrements in task performance (Wertheim 1998). However, there is no empirical evidence to support the idea that longer motion exposure causes increased decrements in task performance or work capacity. Wertheim (1998) has proposed that there are two types of effects resulting from motion, which are 1) general, and 2) specific.

The general effects include motivational, energetic and biomechanical components. Motivational components are due to the psychological and physiological side effects of motion such as sickness, nausea, drowsiness and apathy which result in decreased motivation to complete a task (Wertheim 1998). Energetic components are related to the metabolic demands associated with increased demands to maintain stability while being in motion. The increased energetic demand may be due to increases in co-activation about the joints (Torner, Almstrom et al. 1994), increased stability needs during complex tasks such as lifting (Matthews, MacKinnon et al. 2007; Holmes, MacKinnon et al. 2008), and/or an increase in MIIs that increase the need to correct posture (Wertheim 1998). All would increase the metabolic demands of performing work in motion environments. Indeed, multiple studies have shown that metabolic demands are, in fact, increased in motion environments. Astrand et al. (1973) performed a study that examined the heart rate variation and oxygen consumption in various weather conditions on a vessel at sea during regular fishing outings. Both the heart rate and oxygen consumption were increased during rough waters. This came as no surprise and provides information that the higher intensity of the motion, the more MIF that will likely occur. In fact, later work showed that walking on a treadmill during simulated ship motions and walking across a simulator floor during motions, resulted in increased energy expenditure (Wertheim et al. 1998). Wertheim et al. (2002) found that the $\dot{V}O_{2\,Peak}$ is lower in both simulated motion and motions at sea in naive and experienced seafarers, respectively, compared to stable conditions. Further work by Marais et al. (2010) revealed that sitting and standing in motion, irrespective of any locomotion or other tasks, increased metabolic costs when in simulated motion compared to a stable condition. These studies clearly illustrate that the energy demands in motion are greater than those in a stable environment. The final component of the general effects of motion on human performance is the biomechanical component, and this refers to the increased potential to lose balance, primarily due to MIIs (Wertheim 1998). Regaining balance increases energy requirements, hampers with attention of other tasks and increases the risk of injury, all of which can cause demands to psychological and physiological functioning (Wertheim 1998).

Other research has looked at more specific effects of motion, such as those affecting motor, cognitive, or perceptual skills, as well as a combination of more complex skills. However, the problem with examining complex skills is that one cannot determine which specific task or skill component are being affected by the motions. For example, Wertheim (1996) examined how information is transferred on a ship bridge and how it is affected by motion. Because there were many tasks involved in the transfer of information, it was difficult to conclude what exact tasks were affected by motion. Thus, tasks must be broken down and made more basic to make more accurate conclusions about the detrimental effects of ship motions (Stevens et al. 2002).

Error free performance of motor tasks is a staple of safe and efficient physical work, and thus has been the most concentrated area of study. McLeod et al. (1980) studied the influence of ship motion on manual control skills and found that the effects of motion ranged from "virtual destruction" to no effect at all. This study examined three manual tasks that included: 1) a tracking task with an unsupported arm, 2) a tracking task of a supported arm, and 3) a ballistic task involving digit keying on a keyboard. They found that the ballistic task was virtually unaffected, whereas the supported and unsupported tracking tasks both showed decrements during motion. These tasks were relatively short and designed so that fatigue and motion sickness would not affect the results. Motion induced decrements in pen and paper tracing tasks (Crossland et al. 1993) and visuo-motor computer tracing tasks (Wertheim et al. 1995) have been shown. Similar work by Yau et al. (2011) examined trackball performance in simulated motions that represented a large shipping vessel (very low frequency). They found that there was a little learning curve after a 20-minute practice period, and that movement times were significantly longer in motion compared to those in a stable environment. They also determined that the angle of oscillation had no effect on the differences between the motion and control conditions (i.e. roll and pitch movements both resulted in increased movement times). In a more recent study, Grover et al. (2013) examined knee extension and elbow flexion maximal voluntary contraction force, as well as EMG of the knee extensors and elbow flexors. They found that there was a motion induced decrement in both knee extensor and elbow flexor force, and that knee extensor, but not elbow flexor, EMG was decreased in motion conditions. This suggests that the simulated motions provide an inhibitory response to the neuromuscular system resulting in less force generating capabilities.

Mental work on ships has increased and will continue to increase with the introduction of new technologies, reduced manning and reduced experience (due to industry-related retention issues). Therefore, understanding the effect of motion on cognitive function is quite important. Wertheim (1998) summarized that there were no effects of motion on digit adding, radar monitoring, and a variety of visual and cognitive tasks, however, the studies summarized were not described thoroughly in his review.

Further work, focused on stress responses through heart rate variability of participants when performing mental tasks in motion, resulted in no evident changes (Wertheim, Heus et al. 1998). Since executive functioning includes processes involved in accurate skill performance, decision-making, and planning (Logan 2003), it is possible that some aspects of this cognitive function would be affected, while some others may not. Although there appears to be no decrement to relatively simple cognitive functioning in motion environments, it remains unclear whether a reactive cognitive task would be affected by motion.

Similar to mental work, perceptual skill performance is of importance in the offshore industry. Perceptual tasks, which require visual or auditory detection of signals, coincide with the advanced technology used in ship's alarm management systems. Malone (1981) examined a long duration radar monitoring at sea to discover that there were no decrements observed at sea compared to on land. A later study (Wertheim and Kistemaker 1997b) examined whether the discrimination of letters in motion would be impaired. To do so, they got participants to detect when a certain letter was present on the computer monitor. They found that there was no decrement in the detection of large letters; however, there were decrements in the detection of small letters. The authors attempted to explain the decrements by introducing the idea of "visual blur." However, due to the low frequency ship motions, this idea of "visual blur" is quite unlikely (Stevens and Parsons 2002).

Since there are observed decrements in various types of motor task performance and simulated motion (standing, or even sitting) has a higher metabolic demand than a control environment (Marais, Basset et al. 2010), it seems plausible that an increased duration of motion could result in increased decrement due to motion-induced fatigue. However, this information is currently unavailable for review. Perhaps studies that examined other types of environmental perturbations could provide some insight on the current topic.

1.3: Human Performance During Other Environmental Perturbations

It was long believed that whole body perturbations alters vestibular input to the cerebellum, potentially affecting the ability of a person to perform a routine task. However, recent work by Dilda et al. (2012) used galvanic vestibular stimulation to elicit inhibitory input of the vestibular system on the cerebellum (for extensive review of technique, see (Fitzpatrick et al. 2004)) to examine the effect of such input on a variety of motor skills. Interestingly, reaction time and manual tracking were both unaffected by the inhibitory vestibular input, leaving alternative hypotheses to explain the decrements in human performance seen in altered environments. It is of interest to examine other types of perturbations which may result in similar decrements in human performance and find similarities to help explain why decrements in motion occur. Two environments that provide these perturbations include 1) altered states of gravity and 2) whole body vibration (WBV).

1.3.1: Altered Gravity

An environment which requires precise execution of tasks by humans is that of micro- and anti- gravity, during high G-forces and spaceflight, respectively. Slight error in human performance while in these environments can result in serious injury, assest integrity and even death. During parabolic flight which induces states of microgravity, pointing responses are slowed in a timed pointing task (Bock et al. 2003). Bock et al. (2003) also found that reaction times were slowed and there were increases in error rates during a tracking task in periods of microgravity while on a parabolic flight. Similar detrimental effects of dual-task performance, which included an aiming task along with reaction time, were observed during spaceflight (Fowler et al. 2008; Bock et al. 2010). A longer (20 day) spaceflight study by Manzey et al. (2010) examined the performance of a first-order unstable, manual tracking task for the duration of the flight. They found that the tracking error was increased immediately into the space flight, which was not apparent during the middle portion of the flight, but did return toward the end of the flight. The authors suggest that this pattern may be due to: 1) an adaptation to the environment during the first portion of the flight which would decrease the error rate and 2) an increase in general fatigue and a sense of stress due to overworking toward the end of the flight, which would result in increased error again.

Contrary to low levels of gravity, an increased state of gravity has also been shown to have effects on human performance. Studies have shown that states of high G forces cause increases in isometric forces (Bock 1998; Sand et al. 2003; Girgenrath et al. 2005; Guardiera et al. 2007) but have no affect on the displacement of movements of the control stick in a fighter jet. Guardiera et al. (2010) examined the ability of pilots to maintain flight path stability in a +3g centrifuge. They found that pilots had over exaggerated forces, but no difference in the displacement of movements during increased gravity, which potentially affected their ability to perform stable maneuvers at high G forces. Changes in the acceleration of the body induce vestibular input on the cerebellum and decrements in performance were evident less than 100ms into the task (Guardiera, bock et al. 2007), which is before proprioceptive feedback can take place (Chernikoff et al. 1952; Higgins et al. 1970), therefore, it is believed that the major contributor of degradation to performing tasks in altered gravity was due to the vestibular factors. This, however, was not the only explanation for decrements in human performance in altered gravity. An early review of the sensorimotor problems associated with weightlessness by Bock (1998) hypothesized that the decrements in any task performance were due to adaptive restructuring of the sensorimotor system that ties up cognitive resources, which, therefore, are no longer available to support the execution of a specific skill. It was also discussed that contributing factors to the reduction in availability of resources included stressors that accompany this type of environment such as: confinement; high workload; disruption of the sleep-wake-cycle; body instability; and dependence on life support systems. The exact mechanism for the decline in human performance in altered gravity environments remains unclear.

1.3.2: Whole Body Vibration

Understanding the limits of exposure to whole-body vibration (WBV) is rudimentary. Work by Shoenberger (1978) determined that there are considerable angular accelerations of the human body during vibration, and suggested that vibrations are more complex perturbations than once believed. Vibrations can affect the human body in three ways: 1) direct vibration that is transmitted through the body’s base of support (such as the feet if standing, or buttocks if seated), 2) direct vibration of a tool that is in contact with the distal portions of the body that causes the rest of the body to vibrate (such as a handheld tool), and 3) indirectly, the vibration of an object that a person must interact with, without making contact with the actual vibration (such as a vibrating monitor) (Shoenberger 1978). One and a combination of these vibrations have been shown to affect human performance.

Moseley and Griffin (1986) examined the effects of WBV monitor vibration on measures of visual performance and concluded that whole body vibrations resulted in decrements of visual tracking. Harazin (1999) studied the effects of prolonged (1 hour) of WBV on visual acuity and discovered that there was a 30 minute threshold of vibration which resulted in decrements. Ljungberg et al. (2004) measured the subjective difficulty to perform a choice reaction time task. Although the subjects reported the task to be more difficult during WBV, no reports of the quantitative measurement of reaction time (RT) performance were present in the study. Newell and Mansfield (2008) examined 1-20Hz of random vibration in the vertical and fore-aft directions on reaction time performance and concluded that reaction times were slowed in vibration conditions. RT was slowed in response to WBV with seated and standing posture and with supported or unsupported upper limbs. Performance of a timed pegboard task was also observed to decrease as a result of WBV in the horizontal plane (Baker et al. 2010). These effects demonstrate that fine motor skills can be affected by various frequencies of WBV. If vessels exhibit high frequency vibration as a result of the engines, propeller shafts, major pieces of onboard machinery and low frequency motion induced by sea conditions surrounding the vessel, it is likely that human performance will be diminished during ship motions.

1.4: Fatigue

Fatigue is a broad term that encompasses many complex phenomena, and has many different definitions that are dependent upon the context. For example, in a medical context, Rosenthal et al. (2008) states that physiologic fatigue is initiated by inadequate rest, physical effort, or mental strain that cannot be attributed to an underlying medical condition. In a review of the occupational risks and challenges associated with working at sea, Oldenburg et al. (2010) classify the fatigue of seafarers as a psychosomatic disorder resulting from high stress loads and a lack of sleep. Fatigue, in a more physiological context, can be considered as product of both the central nervous system (i.e. the brain and all of the efferent and afferent feedback) and the periphery (i.e. muscles). The primary goal of fatigue is to protect the body from harm (Noakes 2012), which is accomplished by a slowing of the force and speed of contraction by skeletal muscles (Jones et al. 2009) and an emotional limitation of work output (St Clair Gibson et al. 2003). To examine differences between the peripheral and central components of fatigue, the interpolated twitch technique (ITT) has been used extensively (Bigland-Ritchie 1981; Behm et al. 2002c) to determine voluntary activation and evoked contractile properties. In motion, the likely contribution of peripheral fatigue would result from MIIs that cause an individual to contract their muscles to maintain posture (Torner, Almstrom et al. 1994). It is unknown, however, how motion could affect the emotional limitation of the brain on motor task and neuromuscular output.

1.5: Perturbation Effects on Attention and Task Performance

Kahnemann (1973) suggested that a person's ability to maintain attention on a single and/or number of tasks is based on their cognitive resources. It was thought that there are finite pools of processing facilities available within the brain, which can be allocated to execute one or more concurrent tasks. It was originally believed that there was a single type of resource (universally used) but was later modified to account for experimental findings which suggest the existence of multiple resources. For example, it is proposed that there are separate resources related to attention, visuo-spatial processing and movement preparation (Eversheim et al. 2001). The ability of a person to maintain concentrated attention, otherwise known as vigilance, can be assessed through the measurement of various tasks. Vigilance can either improve or diminish an individual's perception (Cohen 1993), which can affect their ability to attend to sensory stimuli. If there are added sensory stimuli (i.e. MIIs), it is possible that there would be a diminished ability of a person to perform motor tasks. Although not a mechanical perturbation, a study by Button et al. (2004) assessed the effect of noise and voluntary contraction on vigilance task performance and found that noise and contractions impaired reaction time and vigilance task performance, however neuromuscular fatigue did not have an effect on reaction time or vigilance task performance. Therefore, if mechanical perturbations affect the ability of individuals to maintain attention on task, it is possible that their motor task performance may diminish, regardless of MIF or neuromuscular fatigue that may occur.

1.6: Conclusion

The main reasons for a human to be used to perform any work rather than being replaced by machinery include: 1) perception, which refers to complex processes such as recognition of shapes and movement, classification of objects, and predictions of future system behaviour, 2) intelligent decision making abilities, based on perceived inputs and pre-existing knowledge and training, and 3) execution of adapted motor responses, which require coordination of numerous muscles and the integration of sensory feedback (Bock 1998). Therefore, knowledge of how human neuromuscular and motor task performance in a given work environment is vital to productivity and safety. It is not well understood how ship motions affect human motor task performance. However, there is some literature to show increased metabolic costs, increased coactivation around joints, increased perturbations, and impaired neuromuscular performance in short term (< 2 minutes) simulated hydrodynamic motions, however, the effects of simulated motion on motor task and the reason for decrements in neuromuscular performance are less understood. Furthermore, the effects of more prolonged simulated motion on motor task and neuromuscular performance is unknown.

Chapter 2: Co-authorship Statement

My contributions to this thesis are outlined below:

i) The research idea was in addition to Dr. Scott MacKinnon's Natural Sciences and Engineering Research Council of Canada Discovery grant.

ii) The Virtual Environments for Knowledge Mobilization Project allowed the research team to use the Human Factors Laboratory for the duration of the study.

iii) I recruited all participants, performed all of the experimental procedures, and analyzed all of the experimental data required for this study.

iv) With guidance from Dr. Duane Button, I prepared the manuscript and thesis.

v) Drs. Button and MacKinnon provided constructive feedback on the manuscript and thesis.

Chapter 3: Simulated motion negatively affects motor task but not neuromuscular performance.

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Running Head: Simulated motion induces motor task impairments

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3.1: Abstract

Short duration (<10 minutes) simulated motion leads to motion induced fatigue and subsequently compromises motor task and neuromuscular performance. However, the effects of longer duration simulated motion on motor task and neuromuscular performance and the time frame to recover from these effects are unknown. The purpose of this study to determine 1) how simulated motion affects both motor task and neuromuscular performance over one hour of motion and 2) the time course of recovery from any decrements. Sixteen participants performed two experimental testing conditions; 1) motion exposure and 2) control. The dependent variables for motor task performance were reaction time and visuomotor accuracy tracking and for neuromuscular performance were maximal voluntary contractions, voluntary activation, evoked contractile properties and biceps brachii electromyography of the elbow flexors. The dependent variables were measured pre-, 1, 10, 20, 30 and 58 minutes during, and 1 and 15 minutes post-condition. A repeated measures ANOVA revealed that 1) reaction times were significantly ($p < 0.007$) slowed at all time points in motion, 2) error rates of the visuomotor accuracy tracking task were significantly ($p < 0.007$) increased 1 and 10 minutes into motion, and 3) maximal force, voluntary activation, evoked contractile properties and rmsEMG responses of the biceps brachii were unaffected by motion. It is concluded that motion causes an increase in attention demands, which have a greater effect on motor task rather than neuromuscular performance.

3.2: Key Words

Motion, reaction time, visuomotor accuracy tracking, maximal voluntary contraction, electromyography, voluntary activation.

3.3: Introduction

Error-free motor task performance is an integral part of an individual's ability to do manual work. There are only a few studies illustrating that while being exposed to a simulated moving environment for very short periods of time, motor task performance is compromised. For example, acute simulated motion decreases an individual's ability to perform: pen and paper tracing tasks (Crossland and Lloyd 1993), computer tracing tasks (Wertheim, Heus et al. 1995) and trackball tasks (Yau, Chao et al. 2011). Whereas the aforementioned studies determined the effects of acute simulated motion on motor task performance, it remains unknown how longer duration simulated motion would affect motor task performance.

The associated reduction in motor task performance during simulated motion may be due to postural perturbations. Acute simulated ship motion increases postural perturbations, resulting in balance loss (also known as motion-induced interruptions) (Wertheim 1998). While in motion, the increased perturbations contribute to increased co-activation of muscles surrounding the joints (Torner, Almstrom et al. 1994), muscle activation during manual materials handling (Matthews, MacKinnon et al. 2007) and lifting tasks (Holmes, MacKinnon et al. 2008), and increases in the metabolic demands during walking, sitting and standing tasks (Heus 1998; Wertheim, Kemper et al. 2002; Marais, Basset et al. 2010).

Acute, simulated ship motion also leads to impairments in neuromuscular performance. Grover et al. (2013) found that just two minutes of exposure to simulated motion while seated lead to 13.5 and 25.1% decreases in elbow flexor and knee extensor maximal voluntary contraction (MVC) forces, respectively, along with a 13.3% decrease in vastus lateralis electromyography (EMG) during the MVCs. However, they did not observe changes in knee extensor or elbow flexor voluntary activation during the acute motion.

Based on the aforementioned past research, the increased postural perturbations while seated or standing may lead to an increase rate of cognitive and neuromuscular fatigue. In fact, the degradation in a person's motor task performance while in motion may be related to a phenomenon known as motion-induced fatigue (MIF), or, both central and peripheral fatigue resulting from continuous and long-term exposure to motion environments (Wertheim 1998). Until now, MIF has only been characterized by increased energy expenditure during sitting, standing and walking (i.e. via indirect calorimetry) (Wertheim, Heus et al. 1995; Wertheim, Heus et al. 1997a; Heus 1998; Wertheim 1998; Wertheim, Heus et al. 1998; Wertheim, Kemper et al. 2002; Marais, Basset et al. 2010) during acute simulated ship motions. To our knowledge, no studies have examined if MIF, in part, has a neuromuscular fatigue component as well. Since simulated ship motion increases both muscle co-activation and metabolic demands during lifting tasks, as well as decreases the ability to exert maximal force, it is plausible that simulated platform motions may, in part, lead to neuromuscular fatigue, especially if the simulated motion was of a longer duration.

The objectives of the current study were to determine: 1) the effect of simulated ship motion on motor task and neuromuscular performance during one-hour simulated motion exposure and 2) if there was an effect, the time course for recovery from any decrements. Based on previous work in acute simulated ship motion, it was hypothesized that reaction time (RT) and visuomotor accuracy tracking (VAT) performance would have been negatively affected by simulated motions and that maximal force, voluntary activation, evoked contractile properties and biceps brachii EMG would also be impaired (i.e. motion-induced neuromuscular fatigue). It is also hypothesized that the negative effects of motion on motor task and neuromuscular performance would increase as the duration of motion became longer and not fully recover within 15 minutes after the termination of the platform motion. A portion of the current results has been published elsewhere in abstract form (Pearcey et al. 2014).

3.4: Methods

3.4.1: Participants

Sixteen healthy university aged participants (stature 179.0 ± 8.2 cm, mass 88.4 ± 12.3 kg, age 22.1 ± 2.8 years) took part in the study. Participants were verbally informed of all procedures, and if willing to participate, read and signed a written consent form. A signed questionnaire on motion sickness susceptibility (Golding 2006) and a physical activity readiness questionnaire (CSEP 2003) were completed by all participants prior to the start of the study. They were instructed to refrain from heavy exercise 24 hours before testing and followed the Canadian Society for Exercise Physiology (CSEP 2003) preliminary instructions (no eating, drinking caffeine, smoking, or drinking alcohol for 2, 2, 2, or 6 hours, respectively) prior to the start of testing. One participant felt sick within the first 5 minutes of testing due to the motions and was removed from the study. The Memorial University of Newfoundland Interdisciplinary Committee on Ethics in Human Research approved the study (20140562-HK) and was in accordance with the Tri-Council guideline in Canada with full disclosure of potential risks to participants.

3.4.2: Experimental Procedure

Participants undertook two experimental conditions in a randomized order; 1) motion (MO), and 2) no motion (control (CO)) on a motion platform for 1.5 hours. Sessions were separated by 48-72 hours. At the beginning of each session, the participant's maximal resting elbow flexor twitch force was determined. The participant then performed a maximal voluntary contraction (MVC) of the elbow flexors. Prior to any further testing, a visuomotor accuracy tracking (VAT) task was digitally created to produce a double sine wave that reached 25 and 50% of the MVC force. The participant then practiced this task for 10 trials. The participant was also required to practice a visual reaction time (RT) task for 10 trials. After the practice trials, RT and VAT were measured and used as the pre-condition values. All dependent variables were then measured at 1, 10, 20, 30 and 58 minutes during each condition (MO and CO), as well as 1 and 15 minutes post-condition (Figure 1). Dependent variables were always measured in the following order: 1) RT, 2) VAT, and then 3) MVC/interpolated twitch technique (ITT) in an attempt to minimize any effects of the MVC/ITT on the other measurements. Throughout the duration of each condition, the participant sat in a modified ship's bridge chair, which was mounted securely on the motion platform with the hips, knees and right elbow flexed at 90º (Figure 2A).

3.4.3: Independent Variable (Motion)

The kinematics relating to the simulated platform motions were similar to previous experiments performed in this laboratory (Duncan, MacKinnon et al. 2010; Marais, Basset et al. 2010; Duncan, MacKinnon et al. 2012) and simulated motions were modeled after an inshore fishing vessel sailing in rough water. These motion profiles were replicated using a six degrees-of-freedom (dof) ship motion simulator (SMS) (Moog 6DOF2000E, Moog Inc., East Aurora, NY). A 2m x 2m aluminum platform equipped with 1m high railings along the perimeter was mounted on the SMS. A canopy enclosure eliminated external horizontal and vertical cues from the participant's field of vision (Figure 2B). The six dof SMS produced by a Stewart Platform configuration were sway (linear motion in the horizontal y-direction), surge (linear motion in the horizontal x-direction), heave (linear motion in the vertical z-direction), yaw (angular motion about the z-axis), roll (angular motion about the x-axis) and pitch (angular motion about the y-axis) movements (Figure 3). The maximum motion platform range of motion for sway, surge and heave were 1.001, 0.392 and 0.211g respectively and for yaw, roll, and pitch it was 3.493, 9.803 and 13.73 $°\cdot s^{-1}$, respectively.

3.4.4: Dependent Variables

3.4.4.1: Elbow Flexor Force

To determine the right elbow flexor forces, the participant sat in the chair in an upright posture with hips and knees flexed at 90° and arms resting and secured on arm rests. The wrist of the right arm was inserted into a non-compliant padded strap attached by a high-tension wire that measured force using a load cell (Omegadyne Inc. (Sunbury, OHIO). This set-up was used for measurement of all tasks (Figure 2A). The participant performed isometric MVCs with forces detected by the load cell, amplified (Biopac Systems Inc. DA 150 and analog to digital (A/D) converter MP100WSW; Hilliston, MA) and displayed on a computer screen. Data were sampled at 1000 Hz. The participant was instructed to give a maximal effort and to produce force as quickly as possible. Verbal encouragement was given to the participant during the MVC to provide motivation. The mean force for a 500ms duration was measured 1s into each contraction online using Acqknowledge software (Biopac Systems Inc., Hilliston, MA).

3.4.4.2: Reaction Time

Situated at the participant's eye level, a computer monitor displayed a white screen. The participant was instructed to flex the right elbow to produce brief force against the strap, as quickly as possible, when the screen changed from white to red. The time from the change of colour to the onset of force was measured and recorded through the Acqknowledge software (Biopac Systems Inc., Hilliston, MA). The mean of three reaction time responses was calculated at each data collection interval point.

3.4.4.3: Visuomotor Accuracy Tracking

A computer monitor displayed at the participant's eye level was used to display the task for participants. The Acqkowledge software (Biopac Systems Inc., Hilliston, MA) was used to display a target force and the real-time force applied by the participant. The participant was instructed to trace the target force, as accurately as possible, by applying an isometric elbow flexion force against the strain gauge. The amplitude of the target force (y-axis) was adjusted to a double sine wave, which had forces equal to 0-50% of the elbow flexor MVC. Both the target and actual force appeared at the same time on the monitor and moved from left to right across the screen at a constant speed of 1 $cm \cdot s^{-1}$. As more force was applied, the line representing the actual force would move upward, and as less force was applied, the line would move downward. Error was measured as the mean difference (i.e. tracking differences) between the target and actual lines at each time point. Each test was 30 seconds in duration. The mean deviation (error) between the target force and actual force was calculated online using the Acqknowledge software (Biopac Systems Inc., Hilliston, MA) for the low force (first 15 seconds), high force (second 15 seconds) and total sections (combination of both sections) of the VAT. Figure 4A, 4B and 4C show an example of one subject's attempt to perform the VAT at low, high, and total force, respectively, in a control and motion condition.

3.4.4.4: Voluntary Activation

To evoke a maximal twitch force of the elbow flexors, electrical stimulation was applied to the brachial plexus during rest via adhesive Ag-AgCl electrodes (diameter 10 mm) over Erb's point (anode) and the acromium process (cathode). A constant current stimulator (DS7AH, Digitimer Ltd, Welwyn Garden City, UK) was used to deliver current pulses (200 μs in duration, 100-350 mA in amplitude). The electrical current was continually increased until the elbow flexor resting twitch force plateaued. The current required to produce the maximal twitch force was then used for all of the subsequent MVCs.

To assess the central nervous system's ability to fully activate a contracting muscle, the interpolated twitch technique was used. This technique has been described extensively (Bigland-Ritchie 1981; Behm et al. 2001; Behm et al. 2002b). In this experiment, the ITT was performed with three evoked doublets at three-second intervals throughout a ten second data collection trial. The doublets resulted in twitches that were 1) at rest prior to contraction (resting twitch (RT)), 2) during the MVC (superimposed twitch (SIT)) and 3) at rest immediately after the contraction ended (potentiated twitch (PT)). A double rather than a single stimulus was used to increase the signal to noise ratio (Behm et al. 1996). An interpolated twitch ratio was calculated comparing the amplitude of the superimposed twitch force with the potentiated twitch force to estimate the extent of muscle activation during a voluntary contraction (100% - [superimposed doublet force/potentiated doublet force x 100] = % muscle activation) (Behm, St-Pierre et al. 1996). See figure 5A for an example force trace from an ITT protocol used in this study.

3.4.4.5: Electromyography

Electromyography (EMG) was recorded from the biceps brachii muscle during the MVC/ITT protocol. Surface EMG recording electrodes (MediTrace Pellet Ag/AgCl electrodes, disc shape, and 10 mm in diameter, Graphic Controls Ltd., Buffalo, NY) were placed 2 cm apart (centre to centre) over the mid-muscle belly of the muscle of interest. A ground electrode was secured over the lateral epicondyle. Thorough skin preparation for all electrodes included shaving hair, removal of dead epithelial cells with abrasive sand paper, followed by cleansing with an isopropyl alcohol swab on the desired skin area above the superficial muscle. An inter-electrode impedance of < 5 kOhms was obtained prior to recording to ensure an adequate signal-to-noise ratio. EMG signals were amplified and filtered using a 3-pole Butterworth with cutoff frequencies of 10-500 Hz. All signals were analog-digitally converted at a sampling rate of 1 KHz using a MP150 (Biopac Systems Inc. DA 150 and analog to digital (A/D) converter MP100WSW, Hilliston, MA). To determine the changes in muscle activation, the root mean square (RMS) of the biceps brachii EMG was determined for 1s prior to the superimposed twitch during the MVC/ITT. EMG for the biceps brachii during all MVCs throughout the condition was normalized to the respective pre-condition MVC.

3.4.5: Statistical Analysis

All statistics were performed on SPSS (SPSS 18.0 for Macintosh, IBM Corporation, Armonk, New York, USA). Assumptions of sphericity were tested using Mauchley's test and if violated, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity. A one-way repeated measures ANOVA was used to determine within condition effects over time on the RT and VAT tasks during the practice trials. Paired samples two-tailed t-tests with a significance level at $p = 0.05$ were used to determine if there were any differences between pre-MO and -CO measurements for all dependent variables. A one-way repeated measure ANOVA was used to determine with in condition effects over time for all dependent variables Paired samples t-tests were used to examine within condition differences. Due to the large number of hypotheses tested, a bonferoni correction was used to limit the Type I error (Howell 2002). The correction produced a significance level at $p = 0.007$ (0.05/7) for the RT and VAT tasks and level at $p = 0.008$ (0.05/6) for force, voluntary activation and EMG. Cohen's *d* effect size (ES), was calculated to compare changes in RT, VAT error, force, voluntary activation and EMG. Descriptive statistics in text and figures include means ± SE.

3.5: Results

3.5.1: Pre-condition Measurements

No practice trial differences in RT were observed from trial 1 to 9 or 9 to 10 for MO or CO (*p* values ranged from 0.254 to 0.751). However during the VAT task, decreases of 34 ($p < 0.001$), 32 ($p < 0.001$), and 32% ($p < 0.001$) in error were observed for the low, high and total force sections, respectively, between practice trials 1 and 9, and decreases of 36 ($p < 0.001$), 26 ($p < 0.001$), and 34% ($p < 0.001$) in error were observed between practice trials 1 and 10. No significant differences were observed between practice trials 9 and 10 (*p* values ranged from 0.233 to 0.834).

Pre-condition measurements between MO and CO were compared for each of the dependent variables. A two-tailed t-test revealed that the RT ($p = 0.453$) task, low ($p = 0.583$), high ($p = 0.425$) and total ($p = 0.484$) sections during VAT task error, elbow flexor MVC force ($p = 0.439$) and voluntary activation ($p = 0.391$) and rmsEMG of the biceps ($p = 0.573$) did not differ between pre-MO or -CO measurements, indicating that baseline measurements between condition were similar.

3.5.2: Reaction Time

Paired sampled t-tests showed that there were increases in RT at 1 ($p = 0.006$, ES = 0.96), 10 ($p < 0.001$, ES = 1.6), 20 ($p = 0.002$, ES = 1.07), 30 ($p < 0.001$, ES = 1.34), and 58 ($p < 0.001$, ES = 1.49) minutes by 18, 29, 20, 25 and 27%, respectively, during MO compared to pre-MO (Figure 6). However, there were no differences in RT at 1 ($p = 0.062$) and 15 ($p = 0.016$) minutes post-MO compared to pre-MO. There were no differences in the RT during CO (p values ranged from 0.104 to 0.914) throughout the time history of the trial.

3.5.3: Visuomotor Accuracy Tracking

For each of the low, high and total sections during the VAT task, mean error was significantly increased at 1 (38.5%, $p = 0.002$, ES = 0.75; 40.4%, $p < 0.001$, ES = 1.03; 39.4%, $p < 0.001$, ES = 0.96, respectively) and 10 (28%, $p = 0.004$, ES = 0.59; 33.4%, $p = 0.006$, ES = 0.82; 30.8%, $p = 0.001$, ES = 0.75, respectively) minutes during MO compared to pre-MO. Although not significant, error rates were increased 17.3% ($p = 0.074$, ES = 0.37), 18.5% ($p = 0.06$, ES = 0.39), 20.2% ($p = 0.071$, ES = 0.43) for the low, 12.5% ($p = 0.088$, ES = 0.3), 15.1% ($p = 0.126$, ES = 0.4), 11.8% ($p = 0.158$, ES = 0.29) for the high and 14.6% ($p = 0.052$, ES = 0.36), 16.6% ($p = 0.03$, ES = 0.4), 14.7% ($p = 0.063$, ES = 0.36) for the total force sections at 20, 30, and 58 minutes, respectively. Fifteen minutes post-MO, mean error was significantly reduced by 26.5 and 20.8% from pre-MO during the low ($p = 0.001$, ES = 0.56) and total ($p < 0.001$, ES = 0.51) sections, respectively, but not during the high ($p = 0.008$, ES = 0.41) section.

During CO, there were decreased error rates for the low section at 58 (19.8%, p = 0.001, ES = 0.78) minutes and 1 (21.7%, p = 0.006, ES = 0.86) and 15 (22.3%, p = 0.001, ES = 0.88) minutes post-CO compared to pre-CO. There was also a significant decrease in error rate for the total section at 15 (20.9%, $p < 0.000$, ES = 0.53) minutes post-CO compared to pre-CO. The high force section of the VAT task had no significant differences in error rates during CO (p values ranged from 0.192 to 0.95) when compared to pre-CO (Figure 4).

There were significantly greater error rates during both CO and MO during the high than low force sections of the VAT. High force section error rates during CO were 53.4, 58.2, 42.2, 38.9, 35.2, 31, 53.7, 79.2% ($p = 0.001$, $p < 0.000$, $p < 0.000$, $p < 0.000$, $p = 0.001$, $p < 0.000$, $p < 0.000$, $p < 0.000$) greater at pre-CO, 1, 10, 20, 30, 58 minutes, post-CO 1 minute and post-CO 15 minutes, respectively than the low force section error rates. High force section error rates during MO were 45.1, 64.9, 71.1, 82.9, 44.8, 67, 64.8, 69.7% ($p = 0.002$, $p < 0.000$, $p < 0.000$, $p < 0.000$, $p = 0.004$, $p < 0.000$, $p < 0.000$, $p < 0.000$) greater at pre-CO, 1, 10, 20, 30, 58 minutes, post-CO 1 minute and post-CO 15 minutes, respectively than the low force section error rates.

3.5.4: MVC Force, Voluntary Activation and Electromyography

There was no significant main condition x time interaction ($p = 0.479$) or condition ($p = 0.769$) effects but there was a significant main effect for time ($p = 0.036$) of the MVC force output. In both groups, elbow flexor MVC force output was significantly less at one-minute post-MO and –CO by 13.8 ($p = 0.001$) and 14.4% ($p = 0.001$), respectively (Figure 7). There were no within condition effects in elbow flexor voluntary activation (Figure 5B), potentiated twitch amplitude, or mean rmsEMG of the biceps brachii.

3.6: Discussion

This was the first study to examine the effects of longer motion exposure durations (i.e. >10 minutes) of simulated ship motions on motor task and neuromuscular performance. The most important findings from the current study were: 1) RT was immediately increased due to exposure to motion with no further increases during the one hour of motion but recovered immediately upon cessation of the motion, 2) visuomotor tracking ability was immediately decreased by motion up to 20 minutes but was no longer significantly affected 20-60 minutes during motion and 3) force output, voluntary muscle activation and evoked contractile properties of the elbow flexors and rmsEMG of the biceps brachii were unaffected by motion. These results suggest that while seated during one hour of simulated motion, motor task performance is negatively affected for at least up to 10-20 minutes (depending on the type of motor task). While seated, MIF has a cognitive but no neuromuscular fatigue component within a hour or motion exposure.

Decrements in motor task performance as a result of an acute moving environment have been shown previously. In the current study we found that during simulated ship motion there were degradations in RT by 18-29%. Until now, the RT of individuals who were exposed to simulated ship motion, regardless of duration, had not been examined. However, other types of environmental perturbations of various durations in a seated posture have been shown to also increase RT. In a short duration, parabolic flight study, individuals RT was reduced 7-9% pre- to in-flight and then returned to pre-flight values directly post flight (Bock, Abeele et al. 2003). RT tasks during spaceflight were slower by 19 and 21% during simple and dual joystick RT tasks, respectively, but not during a dual stylus RT task compared to control (on Earth) values (Fowler, Meehan et al. 2008)). Acute whole body vibration (WBV) while an individual was seated in various positions resulted in an increased RT by 9-25% (Newell and Mansfield 2008). Finally, individuals who were inverted while seated had 10-12% increases in RT (Smith et al. 2014). Thus, both acute and long duration environmental perturbations affect RT. Based on our findings and others, individuals' RT does not appear to having a learning adaptation and RT remains impaired while exposed to environmental-produced physical perturbations.

Visuomotor accuracy tracking (VAT) error rates in the current study increased by 39-40% and 28-34% at 1 and 10 minutes, respectively and tended to remain increased from 20-60 minutes by 12-20% during the motion exposures. Previous simulated motion studies (Crossland and Lloyd 1993; Wertheim, Heus et al. 1995; Yau, Chao et al. 2011) and other environmental perturbation studies have also shown decrements in various tracking tasks. Guerdeira et al. (2007) examined fighter jet pilots tracking ability during a turning maneuver in a +3Gz centrifuge and found that there were increases in tracking error of ~80%. This study illustrated a larger change in tracking task performance compared to the current findings, which is likely due to the amplitude of the perturbation utilized in their methodology. However, Bock et al. (Bock, Abeele et al. 2003) and Manzey et al. (Manzey, Lorenz et al. 2010) found similar changes in tracking task performance as shown in the current study during parabolic and space flight, respectively. Bock et al. (Bock, Abeele et al. 2003) examined a two-dimension computer tracking task during parabolic flight and found that the tracking error increased by ~35% in-flight compared to pre-flight. During a 20-day spaceflight mission, Manzey et al. (Manzey, Lorenz et al. 2010) found that error rates were increased by ~12% at the first measurement in space (4 days in), but error rates no longer increased on days 5, 7 or 18. Following spaceflight, error rates were increased compared to pre-mission by 12-29% until 4 days after the mission. These results combined suggest that unlike RT, whether or not the environmental perturbations are 1-hour or multiple days long, there is a learning adaptation of tracing tasks while in motion or anti-gravity environments.

Although VAT error rates were increased during the motion condition in the current study, 15-minutes post-MO the error rates were decreased compared to pre-MO. On the other hand, VAT error rates were decreased both during and post-CO. Since there are less attention demands in a control or baseline condition compared to a moving environment, performing the VAT task in a control environment may have resulted in an improved learning response. However, when being perturbed, individuals may have increased attention demands, thus diminishing their ability to exhibit learning responses to a task in these types of environments compared to control environments. It is peculiar that there is an increase in VAT but not RT performance throughout the 1-hour duration of motion. It is possible that there was more learning involved during the VAT compared to the RT task. During the practice trials, VAT improved from the first to the ninth trial, with no change thereafter, however, the RT task did not improve over the duration of the ten practice trials. Thus, improvements in RT were likely not possible, whereas the VAT error rates were still improving. Interestingly, upon cessation of motion, VAT error rates were significantly reduced for both MO and CO compared to pre-condition. Although no learning responses were found in the RT task, both the VAT and RT motor task decrements were no longer present immediately post-motion. Similar to parabolic flight (Bock, Abeele et al. 2003), this suggests that individuals regain their ability to perform motor tasks, without delay, upon the cessation of perturbations. This interpretation is likely relevant to short perturbation exposures compared to longer durations (i.e. extended space flight).

To our knowledge there are no studies that have attempted to elucidate the underlying mechanisms for changes in RT and VAT during simulated ship motion. However, studies employing other forms of environmental perturbations may provide some insight on the underlying mechanisms involved in the deterioration of motor task performance. Acceleration of the human body induces vestibular input on the brain via the cerebellum. Since the cerebellum is a major component of the brain responsible for motor control, it is likely that any inhibitory input to the cerebellum could result in compromised motor control. In an altered gravity environment, decrements in motor performance are evident less than 100ms into a task (Guardiera, bock et al. 2007), before proprioceptive feedback can take place (Chernikoff and Taylor 1952; Higgins and Angel 1970), thus, it has been suggested that the major contributor of degradation of motor performance in altered gravity is due to vestibular factors. More recent work has put this suggestion into question. Dilda et al. (Dilda, MacDougall et al. 2012) used galvanic vestibular stimulation to elicit inhibitory input of the vestibular system on the cerebellum (for extensive review of technique, see (Fitzpatrick and Day 2004)), similar to that of accelerations of the body (i.e. motion). With this technique, they examined the effect of inhibitory vestibular input on a variety of motor skills including RT and manual tracking, both of which were unaffected by the input. Since these tasks are affected by altered gravity and other types of motion, it is likely that the vestibular input may not be responsible for the degradation of motor performance. Thus, an alternate hypothesis has emerged as the front-runner to explain the decrements of motor performance in altered environments. Bock (Bock 1998) hypothesized that the decrements in motor performance were due to adaptive restructuring of the sensorimotor system, resulting in overuse of cognitive resources. Therefore, the required resources to support the execution of a specific skill are no longer available. The evidence regarding the influence of these mechanisms is rudimentary, thus the actual physiological mechanism as to why RT and VAT performance in motion is compromised remains unknown.

One hour of simulated motion while seated had no effect on neuromuscular performance measurements (i.e. MVC force, voluntary activation, evoked contractile properties and biceps brachii EMG). This finding was surprising since, a previous study (Grover, Johar et al. 2013) found that there were up to ~25% decreases in MVC force and EMG of the elbow flexors and knee extensors after only one minute while seated in motion. The authors attributed their findings to the uncertainty of movement experienced while in a motion environment. Performing exercises in unstable environments (Behm et al. 2010; Behm et al. 2011; Behm 2012) and uncertainty of movement (Kornecki et al. 1994) have been shown to cause decrements in maximal force output and voluntary activation. In an unstable environment an individual is at risk of losing balance and/or losing control during the task at hand. Consequently, there is an increase in muscle function for stabilization rather than mobilization, which may result in decreased force output and voluntary activation (Behm et al. 2002a; Behm, Drinkwater et al. 2010; Behm, Willardson et al. 2011; Behm 2012). In fact, changes in recruitment patterns of a lifting task have been shown to change in simulated ship motion (Matthews, MacKinnon et al. 2007) which can likely be attributed to the uncertainty of the motion which causes a potential for a fall. Although there may be some uncertainty accompanied by the motion that the participants experienced in the current study, participants were seated comfortably in a chair with arm rests and feet on a box, thus not at serious risk of perturbation (i.e. motion-induced interruptions). Therefore, there is very little instability or uncertainty associated with a person seated in the simulated ship motions used in the current study, and thus neuromuscular performance was not impaired. The discrepancy between the results of the current study compared to Grover et al. (Grover, Johar et al. 2013) is likely due to methodological differences. In their study, the highest peak force of three contractions, separated by 2 minutes rest, was used for analysis on the control condition day. On the motion condition day, however, participants performed 4 MVCs within a single minute of motion (i.e. 1) elbow flexor, 2) knee extensor, then rest ~40 seconds, 3) elbow flexor and 4) knee extensor MVCs) and the average of the knee extensor and elbow flexor MVCs were used for analysis. Due to the lack of rest periods and high volume of isometric contractions, it is possible that the impairment of force output was due to neuromuscular fatigue itself or a combination of both neuromuscular fatigue and motion. Recent work by Halperin et al. (Halperin et al. 2014) has shown that contractions of the upper body contribute to fatigue of the lower body or vice versa. Also, decrements in force can occur following as low as 3 MVCs with ~5 minutes of rest between MVCs (Wadden et al. 2012). Therefore, the methods used in Grover et al. (Grover, Johar et al. 2013) may have over-predicted the fatigue (i.e. compromised neuromuscular output), if any, that can be attributed to simulated motion. Since the current study had longer rest time between the majority of MVCs and there was no indication of neuromuscular impairment, the disparity of the findings are likely due to methodological considerations.

Until now, laboratory based studies of MIF have only examined measures of oxygen consumption. A study by Heus et al. (Heus 1998), showed that both walking on a treadmill during simulated ship motions and walking on a ship deck at sea, resulted in increased energy expenditure. Similar work by Wertheim et al. (Wertheim, Kemper et al. 2002) found that the $\dot{V}O_{2\,Peak}$ on a cycle ergometer is lower in both simulated motion and motions at sea in naïve and experienced seafarers, respectively, compared to stable conditions. More recent work by Marais et al. (Marais, Basset et al. 2010) revealed that sitting and standing in motion, irrespective of any locomotion or other tasks, resulted in an increased metabolic cost when in simulated motion compared to a stable condition. The results that showed increased energy expenditure irrespective of voluntary movement in a motion environment relate highly to the current study. The likely cause of this increased energy expenditure is the requirement of a person to maintain postural stability (Wertheim 1998), and is related to the magnitude and frequency of MIIs. However, the abovementioned metabolic MIF studies have not examined the fatiguing effects of motions during more prolonged motions (i.e. > 10 minutes). In the current study, we found motion-induced decrements in RT and VAT, but not in any measurement of neuromuscular performance, however, these decrements were not increased with the duration of motion. Therefore, it is likely that the motion-induced impairment is related to cognitive function (i.e. cognitive fatigue) and not impairment to the neuromuscular system (i.e. neuromuscular fatigue). Notwithstanding, individuals were seated for the entire duration of this study. If they were standing, it is possible that neuromuscular fatigue would be evident.

3.7: Limitations

There were several limitations in the study. The participants in this study were naïve to simulated motion. Since they were not accustomed to ship-like motions, it would have been interesting to determine the effects of several bouts of motion exposure in motor task performance. Individuals such as seafarers, who are accustomed to these motions, may not experience the same decrements or become acclimatized and habituated. During spaceflight, error rates were increased and remained increased throughout the 20 day duration (Manzey, Lorenz et al. 2010) illustrating that even with experience an individual’s ability to perform a motor task is reduced. In the current study participants were seated, which requires less postural adaptations to maintain equilibrium compared to free standing. Simulated motion increases the demand of the skeletal muscles to maintain balance. In previous work, participants were standing in motion, which may have induced neuromuscular fatigue of the postural muscles. However, the aim of the current study was to examine if there were any effects of motion on the central nervous system that would result in neuromuscular fatigue, not fatigue of muscles used to maintain posture in a perturbed environment. Future studies on simulated motion should compare motor task and neuromuscular performance in seated and standing positions.

3.8: Conclusion

The present findings suggest that simulated motions cause 1) compromised RT irrespective of the duration of exposure, 2) initial decrements in visuomotor tracking ability when exposed to motion that are no longer (significantly) present after ~10-20 minutes of motion exposure, and 3) no change in maximal force output and voluntary activation of the elbow flexors during motion. Following motion, there is no residual effect evident because both RT and visuomotor tracking ability are both no longer compromised. Decrements to RT and visuomotor tracking ability are possibly due to ongoing sensorimotor adaptation that results in an overload of cognitive resources. Caution should be used when applying these results to other motor tasks in motion because they have been studied in a seated environment. Further research should examine the effects of performing motor tasks in a standing environment, when persons are under greater perturbation.

3.9: Acknowledgements

The authors would like to thank Dr. Thamir Alkanani and Matthew Minε-Goldring for their technical support. The authors would also like to thank the Natural Sciences and Engineering Research Council of Canada Discovery Grant and the Atlantic Canada Opportunities Agency for their financial support of the research project.

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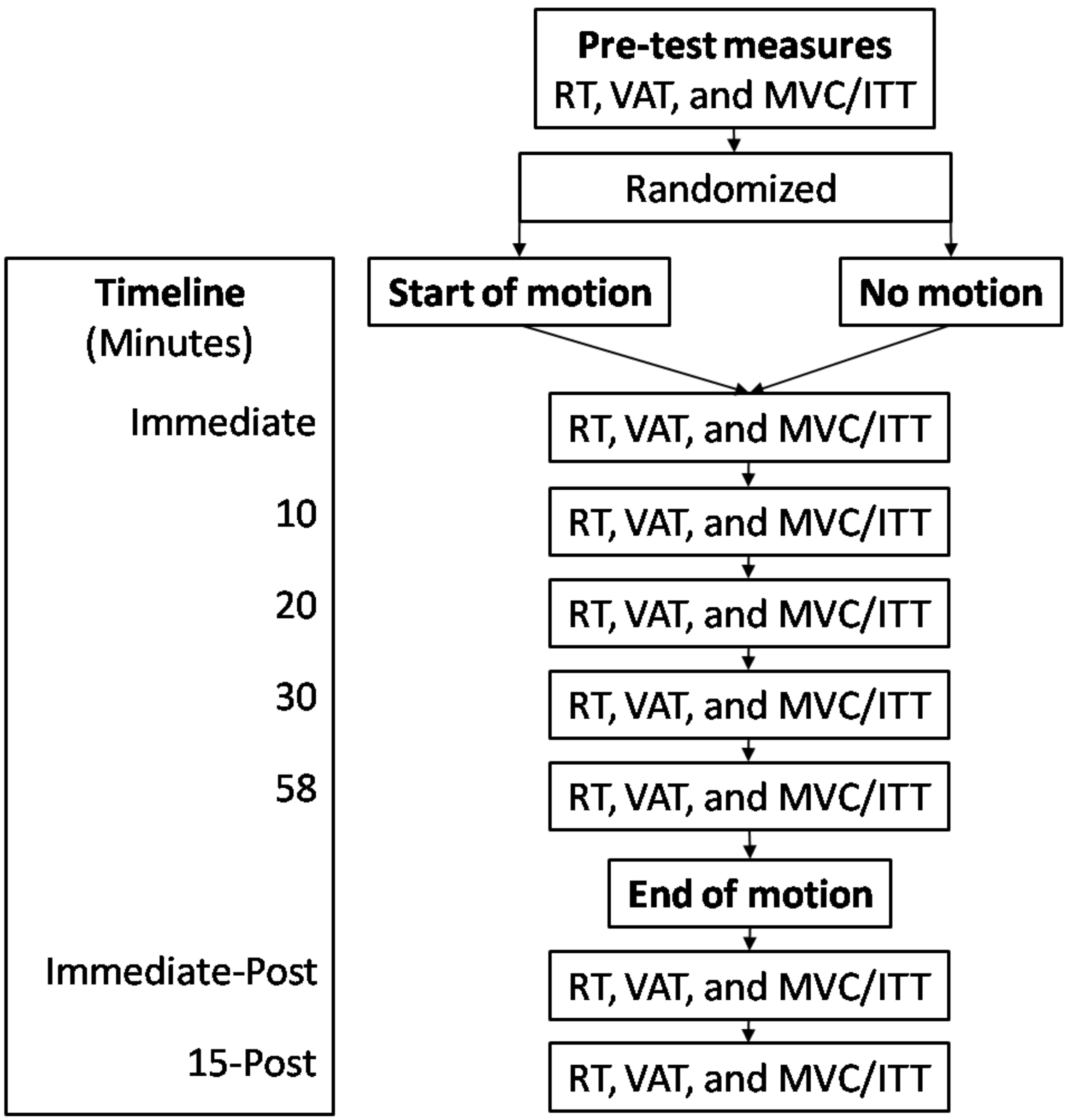
3.11: Figures

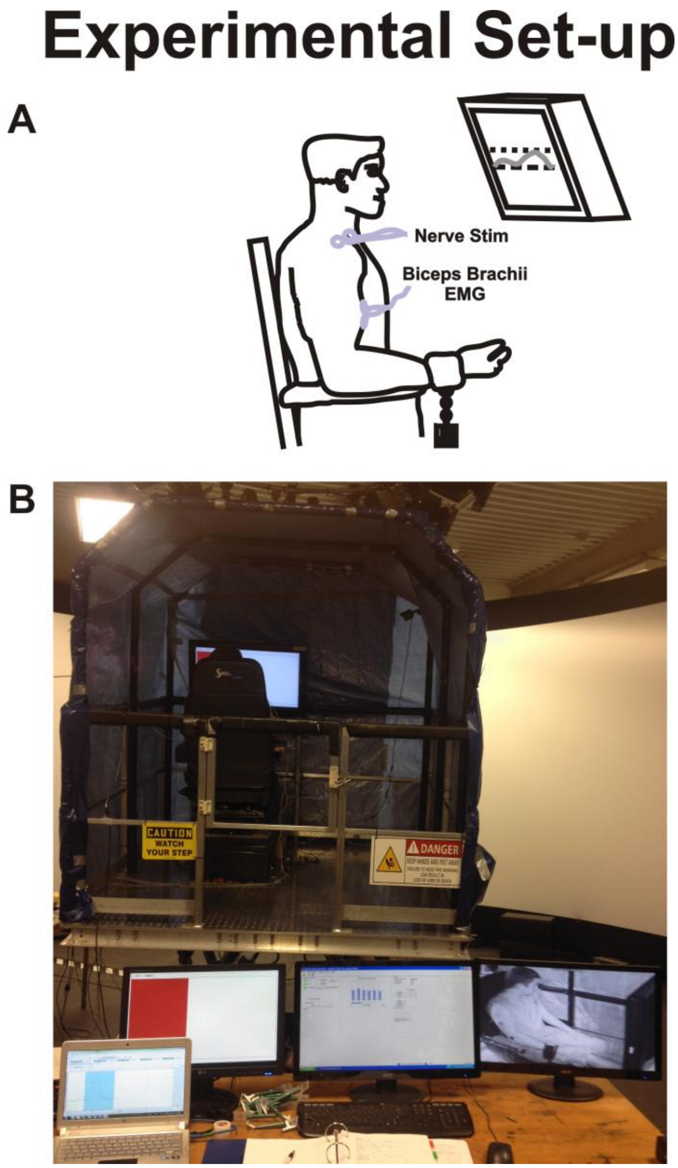
3.11.1: Figure 1 – The Experimental Protocol

The experimental procedure.



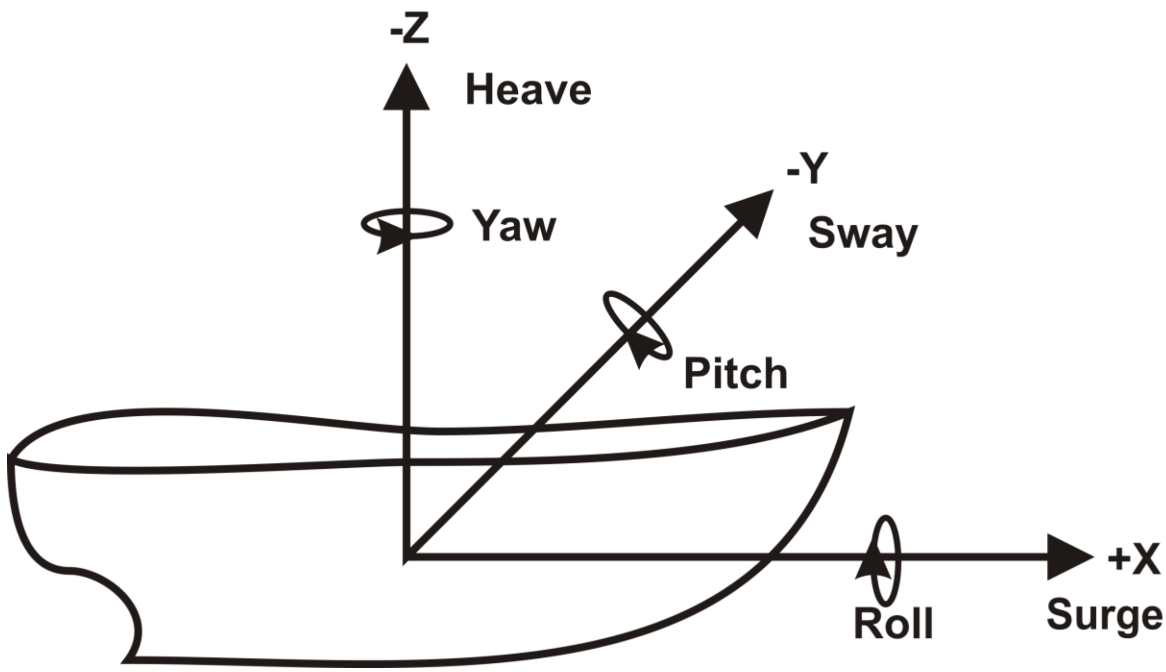
3.11.2: Figure 2 – The Experimental Set-up

Experimental set-up. A) Position of the participant during reaction time testing, visual motor task performance and elbow flexor maximum voluntary contraction. B) A picture of the motion platform.



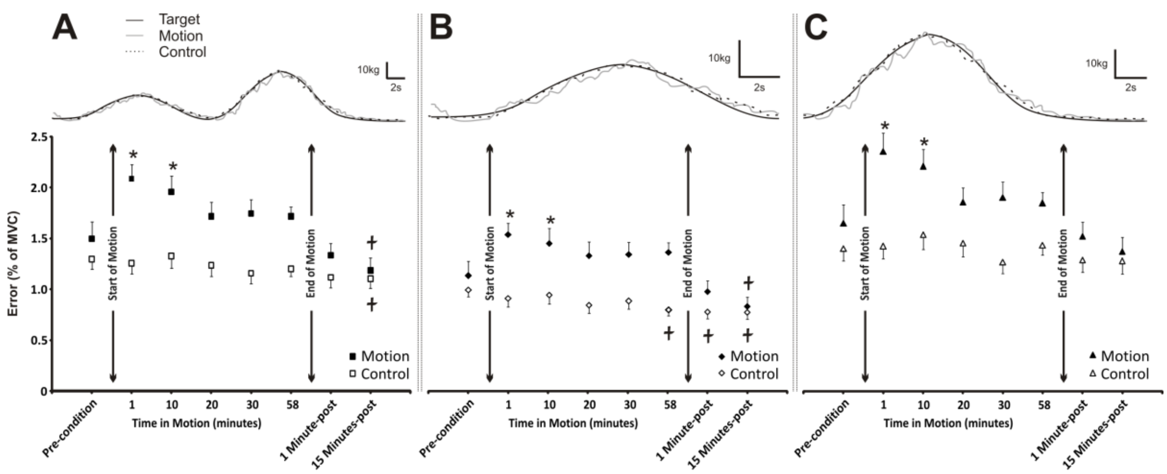
3.11.3: Figure 3 - Six Degrees of Freedom Used by the Motion Simulator

The six degrees of freedom produced by the simulated motion simulator.



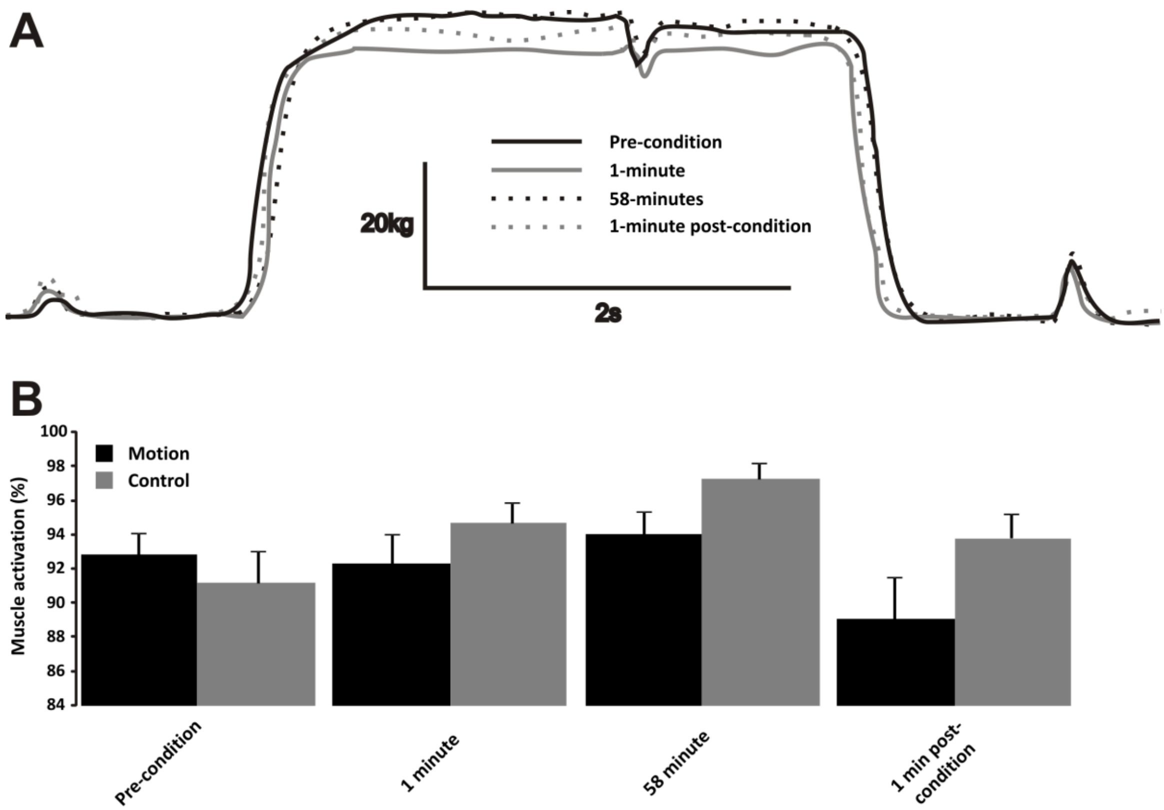
3.11.4: Figure 4 – Visuomotor Accuracy Tracking Results

Visuomotor accuracy tracing (VAT) task recorded during each condition. The VAT task was broken into A) total, B) low, and C) high force sections. Top traces depict a raw data sample of one participants VAT trial (30s) from 10 minutes into each condition. The target trace is the solid black line and actual forces achieved are shown for the motion (grey line) and control (broken black line) conditions. Data points represent group ± standard error. * indicates a significant ($p < 0.007$) increase from pre-condition and † indicates a significant ($p < 0.007$) decrease from pre-condition.



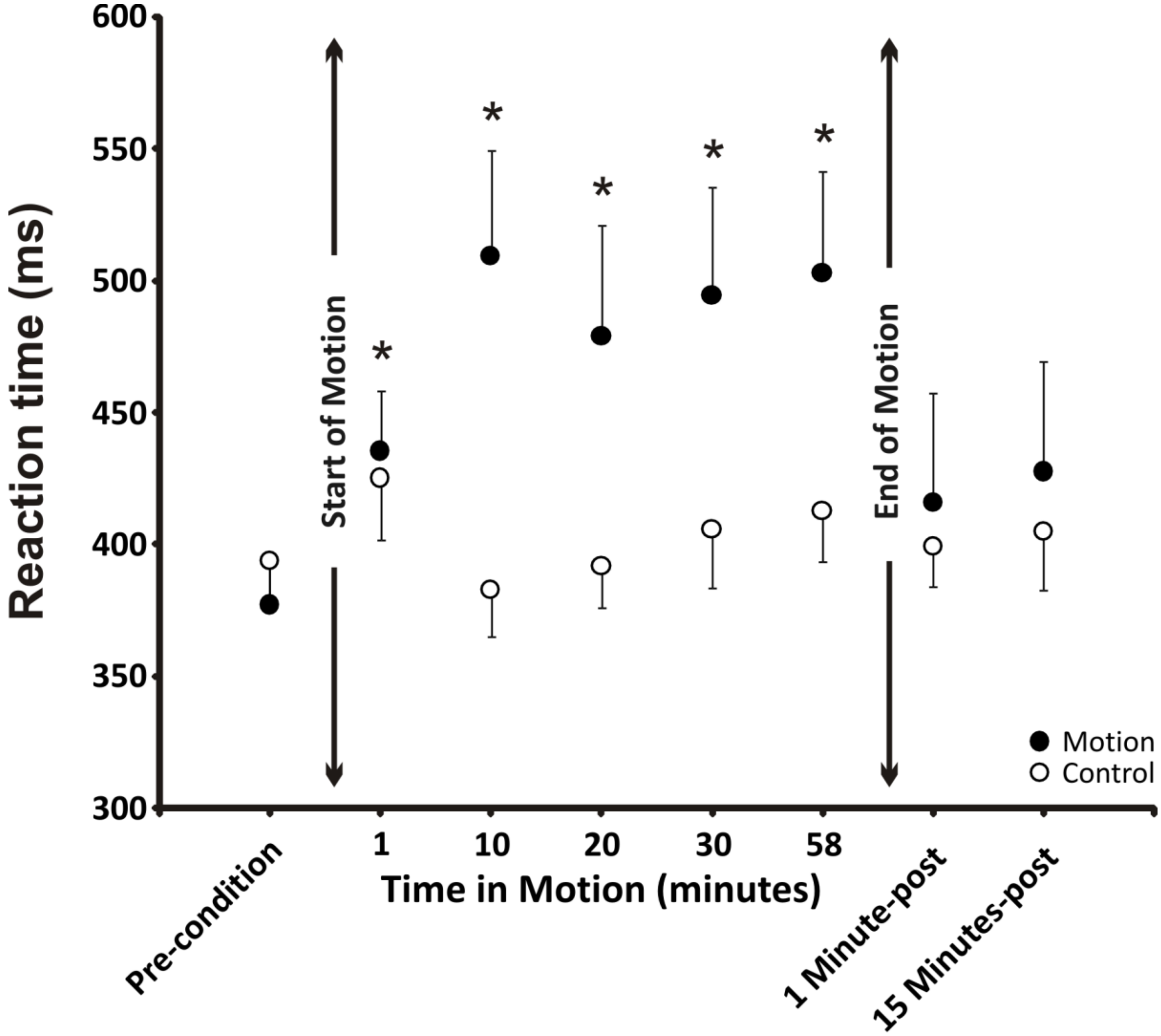
3.11.5: Figure 5 – MVC/ITT Trace

Muscle activation recorded during each condition. A) Maximum voluntary contraction raw data of one participant during the motion condition. Mean B) percentage voluntary activation of the elbow flexors. Bars represent group means ± standard error.



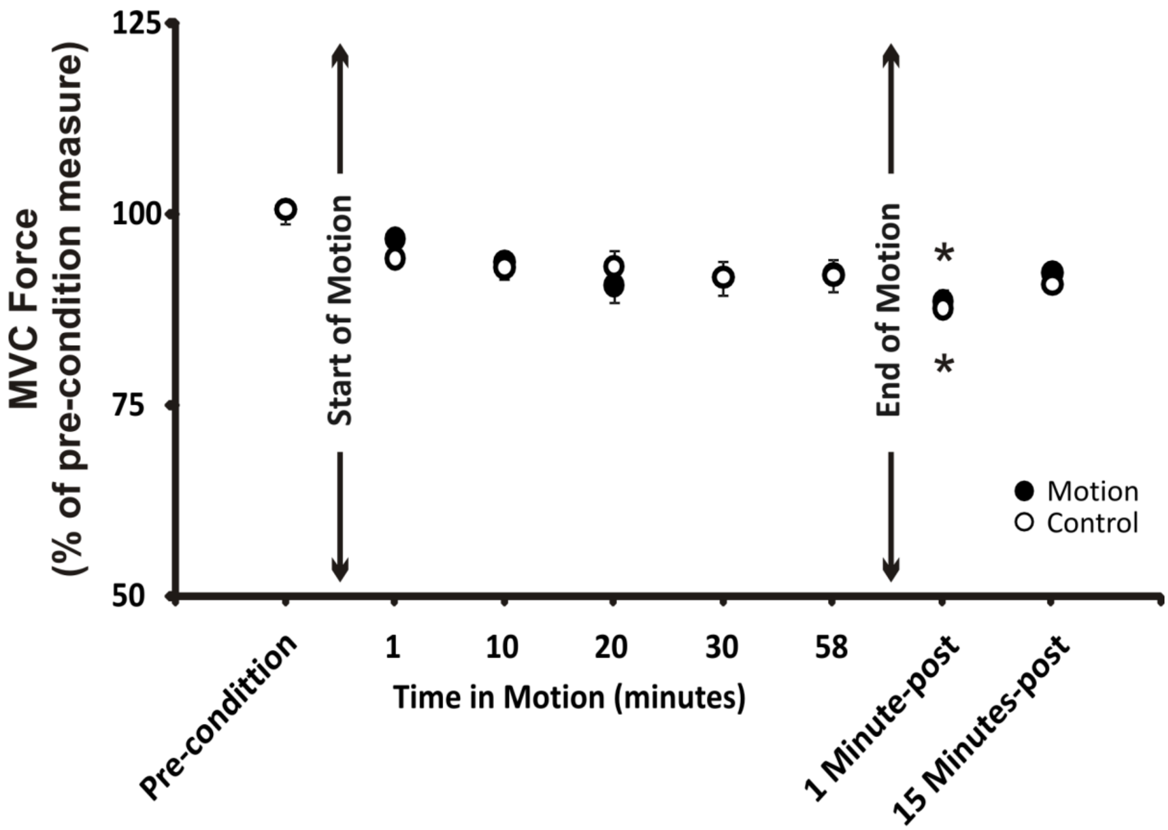
3.11.6: Figure 6 – Reaction Time Results

Reaction time recorded during each condition. Data points represent group means ± standard error and * indicates a significant ($p < 0.007$) difference from pre-condition.



3.11.7: Figure 7 – MVC Force Results

Maximum voluntary force (MVC) recorded during each condition. Data points represent group means ± standard error and * indicates a significant (p < 0.007) difference from pre-condition.



Chapter 4: Summary

Human motor task and neuromuscular performance is vital to productivity and safety in any work environment. However, ship motion effects on human motor task performance are relatively unknown. Literature does exist to show increased metabolic costs, increased co-activation around joints, increased perturbations, and impaired neuromuscular performance in short term (< 2 minutes) simulated motion, however, the effects of simulated motion on motor task and the reason for decrements in neuromuscular performance are less understood. Furthermore, the effects of more prolonged simulated motion on motor task and neuromuscular performance is unknown. The purpose of the current study was to examine the effects of one hour of simulated ship motion on motor task and neuromuscular performance. Results suggest that simulated motion causes 1) compromised RT irrespective of the duration of exposure, 2) initial decrements in visuomotor tracking ability when exposed to motion that are no longer (significantly) present after ~10-20 minutes of motion exposure, and 3) no change in maximal force output, EMG, evoked contractile properties or voluntary activation of the elbow flexors during motion. At the cessation of motion, both RT and visuomotor tracking ability are no longer compromised. We hypothesize that decrements to RT and visuomotor tracking ability are possibly due to sensorimotor adaptation, which causes an overload of cognitive resources. It must be noted, however, that these results may not apply to tasks performed during a standing posture. Future research should examine the effects of performing motor tasks in a standing environment, when persons are under greater perturbation and risk for losing balance.

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Appendix A: Motion sickness susceptibility questionnaire short-form (MSSQ-Short)

Research Project Title: Assessment of human performance on a ship motion simulator

Principal Investigator: Mr. Greg Pearcey, MUN, (709) 864-3138

Supervisor: Dr. Duane Button, MUN, (709) 864-4883

This questionnaire is designed to find out how susceptible to motion sickness you are, and what sorts of motion are most effective in causing that sickness. Sickness here means feeling queasy or nauseated or actually vomiting.

Your childhood experience only (before 12 years of age), for each of the following types of transport or entertainment please indicate:

As a child (before age 12), how often you felt sick or nauseated (tick boxes)

	Not Applicable – never travelled	Never felt sick	Rarely felt sick	Sometimes felt sick	Frequently felt sick
Cars					
Buses of Coaches					
Trains					
Aircraft					

Small Boats					
Ships (e.x. Ferry)					
Swings in Playgrounds					
Roundabouts in Playgrounds					
Funfair rides					

Your experience over the last 10 years (approximately), for each of the following types of transport or entertainment please indicate:

Over the last 10 years, how often you felt sick or nauseated (tick boxes)

	Not Applicable – never travelled	Never felt sick	Rarely felt sick	Sometimes felt sick	Frequently felt sick
Cars					
Buses of					

Coaches					
Trains					
Aircraft					
Small Boats					
Ships (e.x. Ferry)					
Swings in Playgrounds					
Roundabouts in Playgrounds					
Funfair rides					

Appendix B: Free and Informed Consent Form

Title:	Assessment of human performance on a ship motion simulator
Principal Investigators	Greg Pearcey
	School of Human Kinetics and Recreation, MUN
	gpearcey@mun.ca
	Dr. Duane Button (supervisor)
	School of Human Kinetics and Recreation, MUN
	dbutton@mun.ca
Co-Investigator	Dr. Scott MacKinnon
	School of Human Kinetics and Recreation, MUN
	smackinn@mun.ca

You are invited to take part in a research project entitled *"*Assessment of Motion Induced Fatigue on a ship motion simulator.*"*

This form is part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. It also describes your right to withdraw from the study at any time. In order to decide whether you wish to participate in this research study, you should understand enough about its risks and benefits to be able to make an informed decision. This is the informed consent process. Take time to read this carefully and to understand the information given to you. Please contact the researchers, Greg Pearcey or Dr. Button, if you have any questions about the study or for more information not included here before you consent.

It is entirely up to you to decide whether to take part in this research. If you choose not to take part in this research or if you decide to withdraw from the research once it has started, there will be no negative consequences for you, now or in the future. This includes no affect to your grades or academic status.

Introduction

This research is being conducted by Mr. Greg Pearcey as his master's thesis under the supervision of Dr. Duane Button, assistant professor in the School of Human Kinetics and Recreation at Memorial University. This research is aimed at measuring the decrements in performance that occur with motion-induced fatigue. While at sea, Seafarers perform a lot of physical and mental work. Often the movement from the ship can cause fatigue, a phenomenon referred to as motion-induced fatigue (MIF) which may negatively affect the seafarer's ability to complete a job, thus putting their safety at risk. Unfortunately, research investigating the effects of MIF on human performance is limited. Much previous work suggests that exposure to long duration motion (i.e. MIF) will negatively impact worker's performance and subsequently safety and work productivity. Since regular shift work schedules for seafarers in the offshore shipping industry usually consists of a 6 hours (minimum at a time), and there is not empirical evidence to support MIF, it is unknown what the effects of long duration motion is on human performance.

Purpose of study:

The purpose of this study is to determine the effect of MIF on human performance.

What you will do in this study:

This study will consist of two testing sessions conducted on separate days. The following is a brief description of the techniques being utilized and the protocol for each individual testing session.

TESTING SESSION 1: In this session, you will be asked to complete a number of tasks repeated at various time points for the duration of 1.5 hours. The tasks include: 1) reaction time (RT), 2) visuomotor accuracy-tracking (VAT), 3) maximal voluntary force (MVC) and, 4) interpolated twitch technique (ITT). The maximal voluntary force and ITT protocol will require you to be hooked up to some adhesive electrodes that attach to the surface of your skin that will measure the electrical activity of your dominant biceps muscle. You will receive a small electrical stimulation to your muscle (< 0.5A) at rest, during a maximal contraction of your biceps and then at rest again. There may be a slight amount of discomfort with the stimulation; however it will not be painful. These tasks will take place while you are on a 6 degrees of freedom motion platform. This platform is used to simulate motions of ships at sea, and can be stopped immediately at your discretion with the push of a button that will be at your reach. The first time you complete the tasks, you will be on the motion platform but the platform will not be moving. For the next hour you will be seated in motion. During this one hour, we will ask that you complete the tasks at given time points. During the final fifteen minutes of the experiment, the platform will not be moving and we will ask you to complete the tasks again while not in motion.

TESTING SESSION 2: In this session, you will be asked to do the exact same things as session 1, except there will be no motion of the platform.

Length of time:
Participation in this study will require you to come to a lab located in the Faculty of Engineering at Memorial for two testing sessions. The total time commitment will be approximately 3 hours (session 1: 1.5 hours, session 2: 1.5 hours). You will be asked to not engage in weight training or vigorous exercise prior to all sessions. The following table outlines the testing schedule:

TESTING SESSION	**PROCEDURE**
1	Motion
2	Control

Withdrawal from the study:
You will be free to withdraw from this study at any point up to one year after the study has taken place. To do so you simply need to inform the researchers and you will be free to leave. Any data collected up to this point will not be used in the study and will be destroyed. If you are a student your participation in and/or withdrawal from this study will not in any way, now or ever, negatively impact either your grade in a course, performance in a lab, reference letter recommendations and/or thesis evaluation.

Possible benefits:
It is not known whether you will benefit from participating in this study.

Possible risks:
There are several minor risks associated with participating in this study:

1) Redness or irritation on the skin in the area where electrodes are attached. This is a very normal reaction to these electrodes. It does not leave a permanent mark, with redness disappearing in 1-2 days.
2) Electrical nerve stimulation will cause twitching of the muscles and mild discomfort, but is not painful.
3) You may experience post experiment muscle soreness, simlilar to that following an acute bout of exercise.
4) Motion may cause interruptions in posture that may cause you to lose balance temporarily. To decrease the risk of injury during all tasks, you will equipped with a fall arrest harness that will secure you if balance is lost.

5) You may experience feelings of motion induced sickness. If you begin to experience feelings of sickness, the simulator will be stopped immediately.

Confidentiality vs. Anonymity

There is a difference between confidentiality and anonymity: Confidentiality is ensuring that identities of participants are accessible only to those authorized to have access. Anonymity is a result of not disclosing participant's identifying characteristics (such as name or description of physical appearance).

Confidentiality and Storage of Data:

a. Your identity will be guarded by maintaining data in a confidential manner and in protecting anonymity in the presentation of results (see below)

b. All data collected for this study will be kept in a secured location for 5 years, at which time it will be destroyed. Paper based records will be kept in a locked cabinet in the office of Dr. Button while computer based records will be stored on a password protected computer in the office of Dr. Button. The only individuals who will access to this data are those directly involved in this study.

c. Data will be retained for a minimum of five years, as per Memorial University policy on Integrity in Scholarly Research after which time it will be destroyed.

d. The data collected as a result of your participation can be withdrawn from the study at your request up until the point at which the results of the study have been accepted for publication (~1year post study).

Anonymity:

Your participation in this study will not be made known to anyone **who is an audience to the results of this study**.

Recording of Data:

There will be no video or audio recordings made during testing.

Reporting of Results:

Results of this study will be reported in written (scientific article) and spoken (local and national conferences and lectures). Generally all results will be presented as group averages. In cases where individual data needs to be communicated it will be done in such a manner that your confidentiality will be protected (i.e. data will be presented as coming from a representative subject). The findings of the current study will also be published in thesis form, which will be publically available from the QEII Library on campus.

Sharing of Results with Participants:
Following completion of this study please feel free to ask any specific questions you may have about the activities you were just asked to partake in. Also if you wish to receive a brief summary of the results then please indicate this when asked at the end of the form.

Questions:
You are welcome to ask questions at any time during your participation in this research. If you would like more information about this study, please contact: Greg Pearcey (gpearcey@mun.ca) or Duane Button (dbutton@mun.ca).

The proposal for this research has been reviewed by the Interdisciplinary Committee on Ethics in Human Research and found to be in compliance with Memorial University's ethics policy. If you have ethical concerns about the research (such as the way you have been treated or your rights as a participant), you may contact the Chairperson of the ICEHR at icehr@mun.ca or by telephone at 709-864-2861.

Consent:
Your signature on this form means that:

- You have read the information about the research.
- You have been able to ask questions about this study.
- You are satisfied with the answers to all your questions.
- You understand what the study is about and what you will be doing.
- You understand that you are free to withdraw from the study at any time, **up to one year after the study**, without having to give a reason, and that doing so will not affect you now or in the future.
- You understand that any data collected from you up to the point of your withdrawal will be destroyed.

If you sign this form, you do not give up your legal rights and do not release the researchers from their professional responsibilities.

Your signature:

I have read and understood what this study is about and appreciate the risks and benefits. I have had adequate time to think about this and had the opportunity to ask questions and my questions have been answered.

☐ I agree to participate in the research project understanding the risks and contributions of my participation, that my participation is voluntary, and that I may end my participation at any time.

☐ I wish to receive a summary of the results of this study Please provide an e-mail address where this summary can be sent: ____

________________________________ ________________________________

Signature of participant Date

Researcher's Signature:

I have explained this study to the best of my ability. I invited questions and gave answers. I believe that the participant fully understands what is involved in being in the study, any potential risks of the study and that he or she has freely chosen to be in the study.

________________________________ ________________________________

Signature of Principal Investigator Date