Interactive Effects of Physical and Mental Workload: A Study of Muscle Function, Capacity and Exertion Type

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Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
In
Industrial and Systems Engineering

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May 27, 2011
Blacksburg, Virginia

Keywords: physical workload, mental workload, physiological responses, performance

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ABSTRACT

Workers experience combined physical and mental demands in their daily jobs, yet the contribution of these concurrent demands in the development of work-related musculoskeletal disorders (WMSDs) is not clearly understood. There is a need to understand how concurrent demands interact with different work parameters, such as force levels, muscles employed, and types of exertion, to influence physiological responses. Furthermore, whether muscle capacity is altered with these concurrent demands remains unclear. The current research was conducted to address these needs through three experimental studies that evaluated changes in physiological, performance, and subjective measures.

The first study investigated muscle-specific responses to concurrent physical and mental demands during intermittent static work. Mental demands adversely affected physiological responses with increasing physical demand. Furthermore, greater motor and mental performance impairment was observed at either end of the physical demand spectrum. Finally, these interactions were muscle-dependent, with postural (shoulder and torso) muscles indicating a greater propensity to interference due to concurrent demands than executive (wrist) muscles.

The aim of the second study was to evaluate differential effects of exertion type (static and dynamic) during concurrent physical and mental work. Concurrent physical and mental demands adversely affected physiological responses during static exertions compared to dynamic exertions. Furthermore, static exertions were more susceptible to decrements in muscle output and mental task performance than dynamic exertions, specifically at higher force levels.

The last study quantified the effects of concurrent physical and mental demands on muscle capacity (endurance, fatigue, and recovery) during intermittent static work. Additional mental processing was associated with shorter endurance times, greater strength decline, increased fatigability, and slower cardiovascular recovery. Concurrent demand conditions were also associated with higher levels of perceived fatigue, and rapid increases in rates of perceived exertion, time pressure, mental load, and stress.

Overall, the current research provides a comprehensive understanding of the interactive effects of physical and mental demands on physiological responses and task performance. These findings may facilitate the development of task design strategies to help reduce the risk of workplace injuries and to increase worker performance. Finally, outcomes from this research can contribute towards the revision of current ergonomic guidelines to incorporate concurrent assessment of physical and mental demands.

Proposed Publications

The manuscripts presented in Chapters 2-4 are in the process of being submitted for publication in peer-reviewed journals. The author listings for these works are as follows:

1. Mehta, R.K. and Agnew, M.J. (n.d.). *Muscle-dependent responses to concurrent physical and mental workload during intermittent static work*. Manuscript in preparation.
2. Mehta, R.K. and Agnew, M.J. (n.d.). *Exertion-dependent effects of physical and mental workload on physiological outcomes and task performance*. Manuscript in preparation.
3. Mehta, R.K. and Agnew, M.J. (n.d.). *Influence of mental workload on muscle capacity during intermittent static work*. Manuscript in preparation.

Statement of Originality

I hereby certify that all of the work described within this thesis is the original work of the author. Any published (or unpublished) ideas and/or techniques from the work of others are fully acknowledged in accordance with the standard referencing practices.

Ranjana Mehta
May, 2011

Acknowledgements

First and foremost, I would like to thank my mother for being my rock! You are an inspiration to me. Thank you for your unending love, support and encouragement throughout this journey and in my life. To my father, you are my role model. You have shown how dreams can be achieved with relentless efforts under the most inopportune conditions. To both of you, you have always patiently let me follow my dreams, no matter how unusual they seem to be. I am also extremely lucky to have experienced the love and support of my other parents (my mother- and father-in-law). You have been tremendously supportive, loving, and caring – of me and of my dreams.

To my teachers, at Virginia Tech and University of Mumbai, I extend my heartfelt thanks to you for guiding me along the way. I would first like to thank my advisor, Dr. Michael Agnew, for his continuous guidance, patience, and support. I have learned a lot from you that will help me throughout my academic career. I would also like to thank my PhD committee members: Dr. Maury Nussbaum, Dr. Tonya Smith-Jackson, and Dr. Brian M. Kleiner, for their constructive advice and encouragement in my dissertation research. To Dr. Eileen Van Aken, I am extremely grateful to you for giving me amazing opportunities at Virginia Tech to develop my skills as an academic scholar.

To my sisters, Geeta and Meena, you have been my agony aunts! Thank you for being such patient, supportive, and fun sisters! To my brother, Hemant, you are on your way to achieving my dream! Go for it brother! To my other sisters – a.k.a "The roomies", every gossip that you have shared, every rumor that you have created, every secret that you have disclosed, has provided me with much needed distraction from the woes of PhD. You have been my best friends, my supporters, my 24/7 chat buddies – I cannot thank you enough.

I would not have been able to do whatever I wanted to without the support of this one person, who has always been by my side, my husband and my best friend, Ketan. You have been my foundation and have given me the strength to keep pushing throughout this journey. You have selflessly encouraged me to achieve my dreams while sacrificing yours, and your faith in me has never wavered. You are my role model for the person I hope to be, personally and professionally. You have supported me in the most effective way, with humor, be it in your witty ways (yes yes, I admit it!) or when you show your interest in my research (by falling asleep reading my work!). And of course there's *chai*.

Finally to God, I thank you for all the virtues in the world.

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Chapter 1: Introduction

According to Bureau of Labor Statistics (BLS, 2009), there were 348,740 cases of work-related musculoskeletal disorders (WMSDs) in 2009, accounting for ~28% of the total reported non-fatal injuries. The severity of injury associated with WMSDs was determined to be greater than any other nonfatal injury, resulting in 10 median days away from work in 2009, two more days than the median for all days-away-from-work cases. Upper extremity and low back disorders accounted for more than 70% of the total WMSDs, requiring a median of 7 - 21 days away from work. The Bone and Joint Decade (BJD, 2008) estimated that from 2002 to 2004, approximately 30.1% of the U.S. population required medical care due to musculoskeletal conditions. Furthermore, in 2004, the annual costs associated with these injuries was estimated at $127.4 billion dollars (BJD, 2008). In order to reduce these increasing costs and to improve workers' quality of life, efforts are needed to help understand the causes of WMSDs and to facilitate development of ergonomic guidelines and interventions.

The World Health Organization (1985) emphasizes a multifactorial etiology of WMSDs, with physical work demands, psychosocial factors, and individual differences contributing significantly to the cause of the disorder. Physical risk factors, such as repetitiveness, forceful exertions, and static postures, have shown the strongest association to WMSDs (Kilbom, 1994; Malchaire et al., 2001). Psychosocial factors, defined as any factors that are associated with job and organizational environment (e.g., intensified workload, supervisor-employee relation) (Bernard, 1997; NRC, 2001), have consistently been associated with WMSD development (Bongers et al., 2006; Buckle, 1997; NRC, 2001). Individual factors such as age, gender, and personality type have shown to moderate the relationship between physical and psychosocial risk factors and WMSD development (Glasscock et al., 1999; Marras et al., 2000).

While the etiology of WMSDs due to psychosocial factors is not clearly understood, several theoretical models of WMSDs have hypothesized a direct influence of work-related psychosocial factors on biomechanical demands that consequently affects WMSD development (Bongers et al., 1993; Sauter & Swanson, 1996). In particular, intensified workload (measured by indices of mental workload, perceived time pressure, and workload variability) has shown strong associations with musculoskeletal aches and pain symptoms (Pot et al., 1987; Sauter et al., 1983; Theorell et al., 1991). Recent developments in the automation of industrial processes have resulted in workers experiencing increased mental workload in their jobs. Yet, existing research focusing on WMSD development or ergonomic interventions do not address the interaction between mental and physical demands associated with occupational tasks. Thus, the goal of this dissertation research was to address the effects of physical and mental demands on physiological responses. The research is guided by a conceptual model (Figure **1**), adapted from the National Research Council/Institute of Medicine (2001) model of WMSD causation, which proposes that overall workplace task demands (due to combined physical and mental demands) can affect physiological responses and fatigue (worker capacity), which may ultimately lead to the development of WMSDs.

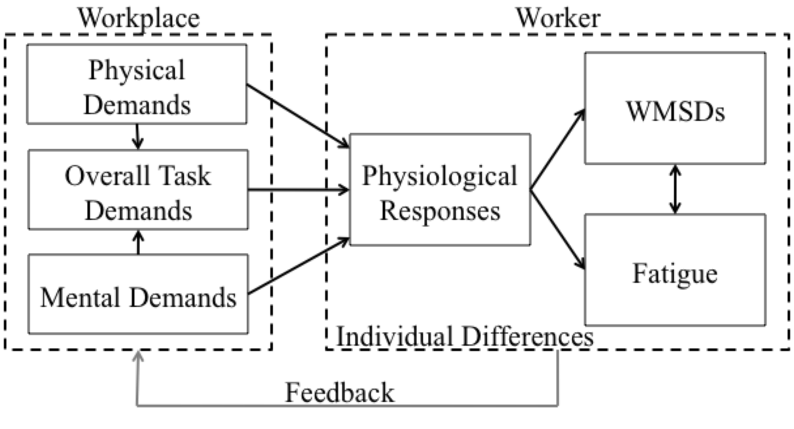


Figure 1. Conceptual model of WMSD development (Adapted from National Research Council/Institute of Medicine model of WMSD causation)

While independent causal relationships between the different types of demand (i.e., physical and mental) and physiological response (illustrated in Figure **1**) have been demonstrated in experimental studies (Carter et al., 2005; Veiersted, 1994), relatively little research, however, has investigated the influence of concurrent physical and mental demands (i.e., overall demands) on physiological measures. Some studies have reported increases in shoulder muscle activity due to mental demands placed on operators during computer work (Laursen et al., 2002; Lundberg et al., 1994; Waersted, 2000; Waersted et al., 1991). The increased muscle activity is suggested to result from co-contraction of the musculature to stiffen a joint, in an attempt to provide additional stabilization (Laursen et al., 1998; van Loon et al., 2001). However, over prolonged duration, increased muscle tension could also lead to the development of WMSDs (Lundberg, 2002; Westgaard, 1999). Much of the research in this domain has focused on jobs requiring minimum physical effort, such as computer work, which are characterized by low-level static exertions. It remains unclear whether this effect is consistent across a range of physical demands. A few studies focusing on higher force levels have reported decreases in shoulder muscle activity during concurrent cognitive processing and maximal and sub-maximal static contractions (Au & Keir, 2007; Macdonell & Keir, 2005). The disparities in the results due to methodological differences have restricted the ability to draw conclusions on these interactive effects. As such, the central theme of this dissertation was to investigate the influence of mental demand on different physical demand levels.

One of the key motivations for this dissertation was to examine the influence of concurrent demands in different work conditions, and that such outcomes may be used in the future to facilitate development of ergonomic guidelines in job redesign. As much of the research in this domain has focused on the effects of concurrent demand on shoulder exertions, it is unclear whether mental demands interact similarly with different work conditions employing other muscles. Since shoulder and low back injuries have most commonly been associated with psychosocial and psychological demands (Bigos et al., 1991; Skov et al., 1996), it is suggested that postural muscle groups are more susceptible to attention-related muscle activity than executive muscle groups (Bloemsaat et al., 2005; Waersted & Westgaard, 1996). However, a few studies have shown similar increases in wrist muscle activity with mental demands (Galen et al., 2002). With the shoulder, wrist, and low back disorders accounting for about two-thirds of the WMSDs (BLS, 2009), it is important to understand whether certain muscle groups have a greater propensity to concurrent demands than others.

Static work has been identified as one of the major physical risk factors contributing to the development of WMSDs (Sjogaard & Jensen, 2006). Thus there is a greater emphasis on employing dynamic exertions to occupational tasks to reduce risk of injuries (Takala, 2002). As a majority of the studies examined the effects of concurrent physical and mental demands during static work, there is a need to determine whether additional mental demands will adversely affect physiological responses when muscles are exerted dynamically. Outcomes from these investigations can provide a better understanding on the effects of concurrent demands for different occupational tasks, which may facilitate job design and ergonomic interventions specific to these tasks.

Despite increasing evidences of the detrimental effects of concurrent demands on physiological responses, existing research have not yet quantified their effects on muscle capacity. It could be argued that continued exposure to combined loads may increase muscular effort (Lundberg, 2002), which may ultimately influence muscle capacity (Figure **1**). Ergonomic tools to determine work demands or work-rest schedules still rely on existing endurance and strength data that account for physical demands alone. Under conditions of physical and mental processing, overall demands can be underestimated and worker capacity may potentially be overestimated. Thus, it is imperative to determine changes in muscle capacity when workers perform concurrent physical and mental work, such that appropriate workload determination or guidelines are based on adjusted capacity and effective administrative controls are employed to further minimize the risk of injuries due to concurrent demands.

The effects of physical and mental demands on low-level static exertions have been widely published. However, to fully understand the contribution of concurrent demands on WMSD outcomes, various work parameters, such as physical workload levels, muscle group employed, and exertion type, need to be taken into consideration. Furthermore, there is a fundamental need to quantify changes in muscle capacity under conditions of physical and mental processing. Based on these research needs, this dissertation consisted of three experimental studies. Study 1 examined physiological changes in three muscle groups due to concurrent physical and mental workload during intermittent static exertions. Study 2 determined exertion-dependent effects of concurrent demands on physiological responses and performance. Finally, Study 3 investigated changes in muscle capacity (endurance, fatigability, and recovery) due to concurrent demands. Each of these three experiments was designed to address the following specific aims:

> **SPECIFIC AIM 1:** To examine changes in physiological, performance, and subjective measures due to concurrent physical and mental workload in three different muscle groups (shoulder, wrist, and torso) during intermittent static work. Three levels of physical workload (low, moderate, and high) were presented in the absence and presence of a mental task.
>
> **SPECIFIC AIM 2:** To determine the effects of exertion type (static and dynamic) and concurrent demands (physical and mental workload) on physiological, performance, and subjective measures. Intermittent exertions (static and dynamic) at three levels of physical workload (low, moderate, and high) were performed in the absence and presence of a mental task.

SPECIFIC AIM 3: To investigate the main and interactive effects of physical and mental workload on muscle capacity during intermittent static work. Three levels of physical workload were assessed (low, moderate, and high) in the absence and presence of a mental task. Endurance time, strength decline, fatigability (changes in physiological, performance, and subjective responses), and recovery (strength and physiological recovery) were assessed.

This thesis is organized in five sections, including this introductory chapter. Chapters 2 and 3 describe the interactive effects of concurrent demands on physiological responses by considering different job parameters, such as physical workload levels, muscle group employed, and type of exertion. Chapter 4 quantifies changes in muscle capacity during concurrent physical and mental work. Chapter 5 summarizes the major findings of this dissertation research and provides suggestions for future work.

The goal of this dissertation research was to quantify short- and long-term neuromuscular changes brought about by concurrent physical and mental demands with different work parameters. Results from this research provide a better understanding of the overall demands placed on workers and resulting effects on physiological outcomes due to concurrent physical and mental work. Certain task parameters were found to be more susceptible to concurrent demands; thus such tasks can be targeted at various phases (during workload determination, job design, or developing ergonomic interventions) where controls, both engineering and administrative, can be employed to reduce the risk of injuries. Finally, outcomes from this research can be used to facilitate revisions of current ergonomic guidelines and tools to address overall demands placed on workers.

Chapter 2: Muscle-dependent responses to concurrent physical and mental workload during intermittent static work

Abstract

Workers experience combined physical and mental demands in their daily jobs, yet the contribution of these concurrent demands toward the development of musculoskeletal injuries is not clearly understood. The purpose of this study was to investigate the interactive effects of concurrent physical and mental workload during intermittent shoulder abduction, wrist extension, and torso extension. Twenty four participants, balanced by gender, performed intermittent static work for three minutes, with a 50% duty cycle, at three levels of physical workload (low, moderate, and high) in the absence (control) and presence (concurrent) of a mental arithmetic task. Physiological responses were assessed using mean electromyographic (EMG) signals, muscle oxygen saturation, and heart rate (HR) measures. Additionally, task performance measures (motor performance and mental arithmetic task performance) and subjective responses (NASA-TLX scores and Borg CR10 ratings) were obtained. Compared to the control, concurrent demand conditions resulted in decreased muscle activity and coactivity, increased cardiovascular load, and impaired motor performance. Furthermore, these outcomes were more prominent at higher physical workload levels and across postural (shoulder and torso) muscles. Performance on the mental task indicated greater interference between physical and mental processing at low and high physical workload levels. Both physical and mental demands adversely affected NASA-TLX scores, however, Borg CR10 ratings were only sensitive to changes in physical demand. These findings may facilitate the development of ergonomic interventions in the workplace, such as overall workload determination and tool and workstation design, that may help reduce risk of workplace injuries as well as avoid worker performance degradation.

Keywords: physical workload, mental workload, physiological responses, performance

Introduction

Work-related musculoskeletal disorders (WMSDs) have been a major cause of disability and decreased productivity in the workplace. In 2009, WMSDs accounted for 28 percent (348,740 cases) of all injuries and illnesses forcing days away from work (BLS, 2009). Upper extremity disorders alone accounted for more than 20 percent of the total WMSDs, with injuries to the shoulder and the wrist resulting in a median of 21 and 14 days away from work, respectively. Furthermore, ~47% of the total WMSDs were attributed to back injuries, leading to 7 median days away from work. Using data from the Medical Expenditure Panel Survey, it was estimated that in 2004, the total cost of all musculoskeletal injuries was $127.4 billion (BJD, 2008). This was a considerable increase in cost compared to the range of $45 to $54 billion that was estimated in 1998 (NRC, 2001).

Musculoskeletal injuries are prevalent in jobs requiring static loads, forceful exertions, and repetitive motions, such as data entry tasks, assembly line work (van der Windt et al., 2000) and manual material handling (Bigos et al., 1986; Spengler et al., 1986). Modifying factors such as intensity and duration further exacerbate the demands placed on workers (Westgaard, 1999). Exposure to psychosocial risk factors at work, such as time pressure and high job demands, may additionally trigger acute physiological stress responses that may lead to impairment of muscular functions (Lundberg, 2002). Psychosocial factors have been defined as the factors associated with job and organizational environment (such as mental and temporal demands), influenced by social context (e.g., supervisor-employee relation, social support) and individual differences (such as personality and genetic factors) (Bernard, 1997; NRC, 2001). Intensified workload, measured by indices of time pressure and mental workload, is one of the most common psychosocial factors that has consistently been associated with WMSDs of the upper extremity and low back (Bernard, 1997). With recent development in automation of industrial processes, tasks involving mental workload are placing additional demands on workers, characterized by abstract thinking, such as mathematical processing and higher order decision-making that are not associated with motor responses.

Numerous experimental studies have reported evidence of physical and psychosocial factors (in particular, mental stress and time pressure) on physiological responses, such as muscle activity, heart rate, and blood pressure. Additional mental demands have been associated with increases in shoulder muscle activity during static tasks, characterized by low-level physical exertions (Waersted et al., 1991; Westgaard & Bjorklund, 1987). According to the Cinderella hypothesis (Hagg, 1991), motor units with low activation thresholds are kept continuously active during low-level sustained contractions. The increase in muscle tension due to additional mental demands during low-level static exertions may result in prolonged low-level muscle activation and as such, cause continuous firing of the fibers associated with these “Cinderella” motor units (Sejersted & Vollestad, 1993). Concurrent physical and mental demands have been associated with activation of the same motor units (Lundberg et al., 2002; Waersted et al., 1996), resulting in decreased micro-pauses (Lundberg et al., 2002; McLean & Quhart, 2002). Along with changes in muscle activity, additional mental stress is associated with increased heart rate and blood pressure (Finsen et al., 2001; Wahlström et al., 2002). However, the effect of mental stress on heart variability (HRV) has yielded conflicting results, with some studies reporting changes in HRV with cognitive stressors (Hjortskov et al., 2004), with others having found no changes (Garde et al., 2002). A few studies have investigated the effects of mental demands on muscle oxygenation, and the results have been inconclusive. Although Heiden et al. (2005) found changes in oxygen consumption of the wrist muscles due to mentally demanding tasks, it is unclear if these changes were attributed to mental demands or increased work intensity.

Much of the research conducted in investigating the effects of physical and mental demands have focused on the shoulder, specifically the trapezius muscle (Lundberg et al., 2002; McLean &

Quhart, 2002). While exploring the differential effects of mental demands on different muscles, Waersted & Westgaard (1996) reported a tendency for higher and more prolonged attention-related muscle activity in the more cranially located muscle sites, namely the neck and shoulder muscles, similar to that found by Fridlund et al. (1986). More recently, proximal muscles were found to be more sensitive to mental workload, while distal muscles responded to increased pacing (Bloemsaat et al., 2005). Despite numerous epidemiological evidences of low back disorders associated with psychosocial factors, only a few studies have reported influence of cognitive challenges on attention-related low back muscle activity and spinal loading (Davis et al., 2002; Marras et al., 2000). The presence of such differential effects of mental demands on different muscle groups (postural versus executive muscles) may imply that certain muscles are more sensitive to attention-related demands than others.

While it has been demonstrated that mental workload adversely affects physiological responses at low-level static exertions, there is a lack of empirical evidence that quantifies this relationship over varying levels of physical workload. A few studies focusing on higher force levels have reported a decrease in muscle activity with mentally demanding tasks (Au & Keir, 2007; Macdonell & Keir, 2005). Therefore, there is a need to quantify the differential effects of mental demands on the spectrum of physical exertion levels, as workers in different occupations experience different demands. Furthermore, it is important to understand whether the interactions between physical and mental demands have differential effects on different muscle groups. With injuries of the shoulder, wrist, and torso muscles accounting for more than 56% of the injuries requiring days away from work (BLS, 2008), it may be beneficial to understand whether certain muscle groups are more sensitive to combined demands than others.

The purpose of this study was to investigate muscle-dependent (physiological and performance based) responses due to concurrent demands, such as physical workload levels and additional mental demands, during intermittent static work. Physiological responses included muscle activity, oxygenation, and heart rate measures. Performance on the physical and mental task, along with perceptions of workload and exertion, were also measured. The hypotheses of the study were, first, that concurrent physical and mental workload conditions would adversely affect physiological, performance, and subjective responses, though the effects will depend on the levels of physical workload. Second, changes observed during concurrent task conditions were hypothesized to be muscle-specific, with shoulder and torso (postural) muscles showing greater susceptibility to concurrent demands than wrist (executive) muscles.

Methods

Experimental Design

A full factorial repeated measures design was utilized to assess the physiological changes due to physical and mental workload during intermittent static exertions of the shoulder, wrist, and torso muscle group. Physical workload (PWL) was induced as percent of maximum voluntary contraction (MVC) of each subject at three levels: low (5% MVC), moderate (35% MVC), and high (65% MVC), covering a range of force levels. Mental workload (MWL) was presented at two levels: absence and presence of a mental arithmetic task. Participants completed three experimental sessions; each experimental session focused on one muscle group to minimize equipment setup time. In order to avoid any potential learning or order effects, balanced Latin Squares were employed to determine the order of the muscle group and the treatment conditions within each muscle group.

Participants

Twenty-four participants, balanced by gender, were recruited from the local community. Mean (SD) age, stature, and body mass of the male participants were 22 (1.9) years, 1.77 (0.11) m, and 75.5 (10.3) kg, respectively, with corresponding values of 23.4 (1.6) years, 1.68 (0.06) m, and 60

(6.9) kg for the female participants. Only those with no injuries or physical disorders within the last one-year were allowed to participate. For ease of experimental setup and preparation, only right-handed participants were recruited. Informed consent, using procedures approved by the Virginia Tech Institutional Review Board (**Appendix A**), was obtained prior to the experiment.

Procedures

The study comprised of four sessions, one preliminary and three experimental sessions. The interval between sessions was at least two days to avoid any fatigue or carryover effects. During each experimental session, participants performed intermittent static exertions at varying physical workload levels, in the absence or presence of the mental arithmetic task.

Preliminary session

During the preliminary session, participants were familiarized with the experimental procedures. A student version of the Jenkins Activity Survey to determine Type A tendencies (Jenkins et al., 1979; Yarnold & Bryant, 1994) was administered. After the familiarization procedure, participants performed a series of MVCs of the shoulder, wrist, and torso muscle groups. For the shoulder muscle group, participants were seated in a dynamometer (Biodex™ System 3 Pro Medical System, Shirley, New York, USA). The Biodex™ system has been proven to be a highly reliable isokinetic dynamometer (Lund et al., 2005), and has also shown to be reliable and valid for measuring position and torque during static exertions (Drouin et al., 2004). Each participant was comfortably secured at the shoulder and waist in a seated position, with their right shoulder abducted at 90° and elbow attached to the dynamometer arms using a padded strap (Figure **2**). Once settled, participants were instructed to maximally abduct their arm against the dynamometer padding, keeping the other arm resting at the side. A minimum of three MVCs were performed, with two minutes rest given between each MVC. The maximum torque obtained from the three MVCs (Nm) was used to determine the PWL levels for the shoulder group.

Figure 2. Participant posture for shoulder abduction (left), wrist extension (center), and torso extension (right).

After adequate rest, participants were prepared for MVCs of the wrist muscle group. They were comfortably secured at the shoulder and waist in a seated position, with their elbow flexed at 90° (with upper arm vertical), forearm strapped to the armrest using a padded strap, with their wrist in a pronated position at 0° (Figure **2**). Similar to the shoulder MVCs, participants were instructed to maximally extend their wrist on a padded strap connected to a load cell (Interface SM-500, Arizona). A minimum of three MVCs were performed, with two minutes rest given between each MVC. The maximum force obtained from the three MVCs (N) was used to determine the PWL levels for the wrist group.

The experimental setup for the torso muscles required participants to stand on a hip fixture (Figure **2**). Participants' hips and legs were securely fastened in a static position using padded straps, leaving their upper body free to conduct torso extension. Each participant's upper back was connected to a padded lever arm of a dynamometer (Biodex^{TM} System 3 Pro) using restraints. Participants were asked to maximally extend their torso against the padded arm, and a minimum of three MVCs were collected, with adequate rest in between. The maximum MVC value (Nm) was used to determine the PWL levels for the torso. For all the muscle groups, the MVCs collected were corrected for gravitational effects acting on the limb and the Biodex™ apparatus.

Experimental sessions

At the beginning of each experimental session, participants were attached to the bioinstrumentation equipment, namely EMG electrodes, near infra-red spectroscopy (NIRS) probes, and a heart rate monitor. Based on the muscle group condition, participants were secured in the biodex™ (for the sessions involving shoulder and wrist muscle group) or the hip fixture (for the session involving the torso muscle group). The experimental setup and postures utilized for the three muscle groups were similar to that employed in the preliminary session.

Experimental task conditions: Once settled, participants' baseline EMG, muscle oxygenation, and heart rate measures were collected for 2 minutes. Based on the order of the treatment conditions, participants performed intermittent static exertions that comprised of repetitions of 5 s of static exertion followed by 5 s of rest. To present different PWL conditions, a computer screen was placed at eye height, displaying the torque feedback for each level of PWL. The visual feedback was presented as a series of square waves displaying work and rest periods, thereby visually controlling the duration of the work-rest cycle. For each control condition (i.e., only physical task with no concurrent mental arithmetic task), at 5%, 35%, and 65% MVC, participants were instructed to track their exertion levels with the visual feedback, for the duration of three minutes. For the concurrent task conditions (i.e., both physical and mental task), participants were asked to concurrently perform mental arithmetic test while performing the intermittent static exertion for three minutes. Specifically, multiplication problems involving a two-digit number (from 11-49) and a one-digit number (2-9) were verbally presented during each rest phase, and participants were instructed to verbally provide an answer during the following work phase. This specific type of mental arithmetic task has been shown to induce psychological stress and evoke distinct physiological responses (Allen & Crowell, 1989; Schleifer et al., 2008). Participants were encouraged to provide accurate answers while maintaining the required force levels, and the performance on the mental task was recorded. To help avoid any fatigue carryover effects, a 6-minute rest break (minimum) was provided after each treatment condition.

Measures

Physiological measures

Electromyography: EMG signals of the participants' muscles were collected at 1024 Hz, using 10 mm, rectangular Ag/AgCl pre-gelled bipolar electrodes. EMG signals from the prime mover muscles for shoulder abduction (middle deltoid), wrist extension (extensor carpi radialis), and torso extension (Erector spinae at the L1, and multifidus at the L4/L5) were collected. In addition, to quantify muscle co-contraction, EMG signals from anterior and posterior deltoid, upper trapezius, and the latissimus dorsi (for the shoulder), flexor carpi radialis, and flexor and extensor carpi ulnaris (for the wrist), and internal and external oblique (for the torso muscle group) were also recorded.

At the start of each session, muscle sites on each subject were shaved and cleansed with alcohol to reduce skin resistance, and electrodes were placed on the muscle sites according to clinical procedures (Perotto, 1994). After 20 minutes of stabilization, a quiet EMG trial was collected to remove signal bias. Raw EMG signals of the trials were corrected for signal bias, band-passed filtered (20-450 Hz), full-wave rectified and subsequently low pass filtered (dual pass, 4th order Butterworth filter with effective cutoff frequency of 3 Hz), using a custom program developed in LabVIEW (National Instruments, TX, USA). MVCs from each muscle site were obtained and EMG data from each muscle were normalized with respect to its maximum value. Mean muscle activation for the prime movers across each muscle group were quantified by averaging the 2nd, 3rd, and 4th second data of each work period for each treatment condition. Coactivity was measured using two measures: co-contraction indices and agonist activation. Co-contraction indices (CCI) of the muscle-pairs ($CCI_{Shoulder}$, CCI_{Wrist}, CCI_{Torso}) were calculated as the ratio of the antagonist muscle with respect to the agonist muscles, multiplied by the sum of the activity of all muscles (Rudolph et al., 2001). In addition, an overall estimate of the EMG activation from the agonist muscles (summation of all agonist muscles) from each muscle group was also determined.

Muscle oxygenation: Muscle oxygenation was measured continuously using a near-infrared spectrometer (NIRS) (OxiplexTS, ISS, Champaign, IL, USA). It is based on the principle of differential absorption properties of oxygenated and deoxygenated hemoglobin in the near infrared range (Heiden et al., 2005). At the start of every session, the system was calibrated according to the manufacturer’s instructions. Muscle oxygenation was sampled at 2 Hz. The NIRS probes were placed on the belly of the prime mover muscle. The muscles being monitored were the middle deltoid for the shoulder group, extensor carpi radialis for the wrist group, and the erector spinae muscle at the L3 level. The absolute value of percent saturation was recorded continuously for the whole trial. The 2nd, 3rd, and 4th second data of each work period was utilized and averaged across each treatment condition to obtain mean oxygen saturation levels.

Heart rate: Heart rate (HR) measures were collected using a heart rate monitor (RS800 Polar Heart Rate Monitor, Lake Success, NY) affixed to the skin near the midpoint of the participant’s sternum. HR data was recorded continuously as beat-to-beat (R-R) intervals, and average HR was calculated for the entire duration for each treatment condition. Heart rate variability (HRV), sensitive to both physical and mental workload (Kalsbeek & Ettema, 1963; Meshkati, 1988), was calculated as the standard deviation in HR over the entire duration (Malik et al., 1996).

Performance measures

Motor performance: Motor performance was measured using variations in force generated by participants for the three muscle groups. Torque output data from the dynamometer were collected for the entire duration of each treatment condition and utilized to compute force fluctuation measures. The torque data were sampled at a frequency of 1024 Hz, low pass filtered at 15 Hz, and the 2^{nd}, 3^{rd}, and 4^{th} second data of each work period was utilized. Force fluctuation from the work periods of each treatment condition were quantified in terms of a coefficient of variation, which represents the fluctuation relative to the mean force (calculated as SD / mean force) (Enoka et al., 2003; Ranganathan et al., 2001).

Mental task performance: Performance on the mental arithmetic task was recorded (number of incorrect answers/no answers), and quantified for each treatment condition.

Subjective measures

Borg CR10 ratings: Ratings of Perceived Exertion (RPEs) of the different body parts were obtained from participants after every treatment condition using the Borg CR10 scale (Borg, 1990) (**Appendix D**). Participants were provided with a description of the 10-point scale, with anchors from “0, nothing at all”, to “10, extremely strong (almost max)”. For all treatment conditions, participants were asked to provide ratings of perceived exertion for their hands and wrists, lower arm, upper arm, shoulder, upper back, lower back, and legs.

NASA-TLX scores: Participants’ perception of workload was assessed using the NASA Task Load Index (NASA-TLX). The NASA-TLX is a multi-dimensional approach to workload assessment that measures subjective workload on six scales: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration (Hart & Staveland, 1988). Participants were asked to rate the level of these sub-scales between 1 (Low) and 20 (High) after the completion of each treatment condition (**Appendix E**). Additionally, they were instructed to perform 15 pair-wise comparisons of the six sub-scales, indicating the sub-scales that contribute the most to the workload of the task. Weighted ratings for each sub-scale were calculated by multiplying each rating by the weight given to that sub-scale by the participant. The individual sub-scale workload measures were used to compare between the different treatment conditions. Overall workload score (scored from 0 to 100) was calculated as the sum of the weighted ratings of each sub-scale, divided by 15 (sum of weights).

Statistical analysis

Repeated measures analyses of variances (ANOVAs) were conducted to determine the main and interactive effects of physical and mental workload on the physiological, motor performance, and subjective measures for each muscle group. Furthermore, one-way ANOVAs to test the effects of physical workload on mental task performance were conducted for each muscle group. For all analyses, gender and order of exposure were included as blocking variables. The effect of the order was found to be non-significant (all $p > 0.05$) for all measures, and was thus removed from subsequent analyses. Item reliability on the Type A scores and NASA-TLX responses were determined using Cronbach's alpha (standardized) values. Cronbach's alphas for all question items in the Jenkins Activity Survey ranged from 0.4 to 0.6 (entire set = 0.496), indicating that Type A scores had low reliability (Nunnally, 1978). Thus, these data were not included as a covariate within the statistical model. Inter-item reliability on all NASA-TLX scores ranged from 0.79 to 0.85 (entire set = 0.85). No substantial violations of parametric assumptions were evident for any of the aforementioned tests, and all statistical analyses were performed using JMP 8.0 (SAS Institute Inc., Cary, NC). Where required, post-hoc comparisons were conducted using Tukey's Honestly Significant Difference test. Statistical significance was determined when $p < 0.05$. All summary values are presented as means (SD).

Results

Significant main and interaction effects obtained on the physiological and performance measures are summarized in Table **1**.

Table 1. Summary of ANOVA results (p-values) for the effects of PWL and MWL on physiological and performance measures. The symbol * indicates a significant effect ($p < 0.05$).

Measures	Muscle	PWL	MWL	PWL x MWL
Mean EMG	Shoulder	<0.0001*	0.038*	0.154
	Wrist	<0.0001*	0.051	0.011*
	Torso	<0.0001*/<0.0001*	0.007*/0.077	0.175/0.023*
CCI	Shoulder	<0.0001*	0.266	0.165
	Wrist	<0.0001*	0.053	0.09
	Torso	<0.0001*	0.105	0.163
Agonist EMG	Shoulder	<0.0001*	0.045*	0.07
	Wrist	<0.0001*	0.037*	0.003*
	Torso	<0.0001*	0.025*	0.041*
% Oxygen saturation	Shoulder	<0.0001*	0.539	0.615
	Wrist	0.001*	0.904	0.554
	Torso	0.001*	0.106	0.15
HR	Shoulder	<0.0001*	0.02*	0.87
	Wrist	<0.0001*	0.038*	0.074
	Torso	<0.0001*	0.012*	0.404
HRV	Shoulder	<0.0001*	0.21	0.51
	Wrist	<0.0001*	0.089	0.009*
	Torso	<0.0001*	0.224	0.04*
Motor performance	Shoulder	0.005*	0.052	0.083
	Wrist	<0.0001*	0.189	0.145
	Torso	<0.0001*	0.018*	0.3
Mental task performance	Shoulder	0.041*	-	-
	Wrist	<0.0001*	-	-
	Torso	<0.0001*	-	-

Note: *p*-values for Torso mean EMG are presented as erector spinae at the L1 / multifidus at the L4/L5.

Physiological responses

Electromyography

A significant main effect of PWL was observed for all EMG measures (mean EMG, CCI, agonist EMG) across all muscle groups with higher physical demands resulting in increased muscle activity and coactivity. Additional mental workload decreased middle deltoid and erector spinae activity by 6.2% and 9%, respectively. Although not significant, extersor carpi radialis (*p* =

0.051) and multifidus ($p = 0.077$) muscle activity also decreased (by 6.7% and 5.4% respectively) during conditions requiring concurrent physical and mental processing. A similar main effect of MWL was found for agonist EMG, with additional mental arithmetic task decreasing agonist EMG for all muscle groups by 4.3 - 7%. The decrease in mean and agonist EMG due to MWL were found to be more prominent at 65% MVC for the wrist and the torso (Figure **3**), and a similar trend was observed for $\text{agonist}_{\text{Shoulder}}$ ($p = 0.07$). Co-contraction indices were not found to be significantly different between the control and mental arithmetic conditions, although a trend was observed during wrist extension ($p = 0.053$), suggesting greater co-contraction in the control condition compared to the mental arithmetic condition.

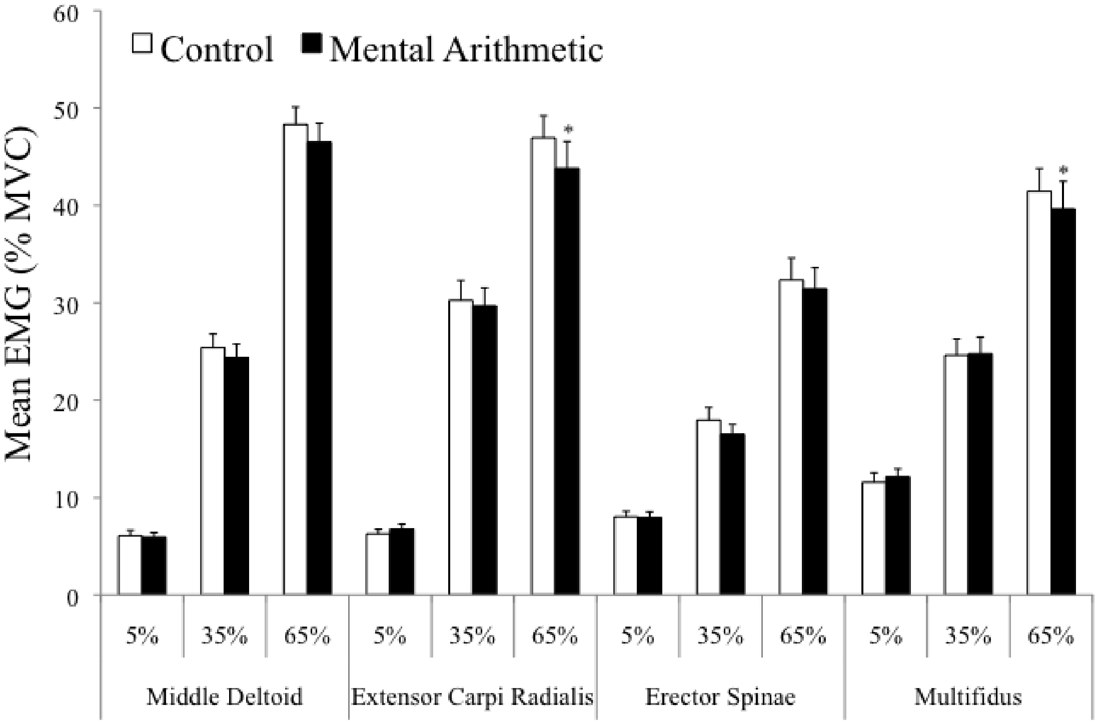


Figure 3. Interactive effects of PWL and MWL on mean EMG of the shoulder (middle deltoid), wrist (extensor carpi radialis), and torso (erector spinae and mutlifidus) muscles. PWL levels are percentages of MVCs (as described in the Methods). Error bars represent standard error. The symbol * indicates a significant difference between the Control and Mental Arithmetic conditions.

Muscle oxygenation

Oxygen saturation decreased with an increase in physical workload levels for all muscle groups (Figure 4). For the shoulder and wrist muscle group, a greater decrease in oxygen saturation was observed at 65% and 35% compared to 5% MVC; whereas in the torso, a greater reduction in saturation was observed at 65% compared to 35% and 5% MVC. MWL and its interaction with PWL did not significantly affect muscle oxygenation in any of the muscle group.

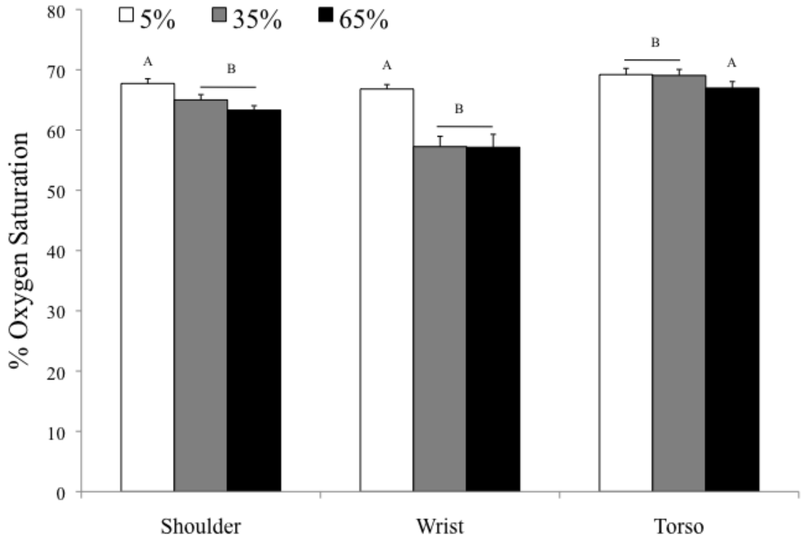


Figure 4. Main effect of PWL on oxygen saturation for the shoulder, wrist, and torso muscle group. PWL levels are percentages of MVCs (as described in the Methods). Error bars represent standard error. Bars not connected by the same letters indicate a significant difference between PWL levels.

Heart rate measures

Average HR increased significantly with increases in PWL, with an increase of 33.7% during shoulder abduction and 25% during torso and wrist extension found from low to high PWL levels. Additionally, MWL significantly increased HR by 2 - 4% across all muscle groups (Figure 5). PWL had a main effect on HRV across all muscle groups, but was not affected by MWL. An interaction effect between PWL and MWL was found for during wrist (*p* = 0.009) and torso (p = 0.04) extension. In general, HRV was higher at 5% and lower at 65% MVC in conditions with additional MWL.

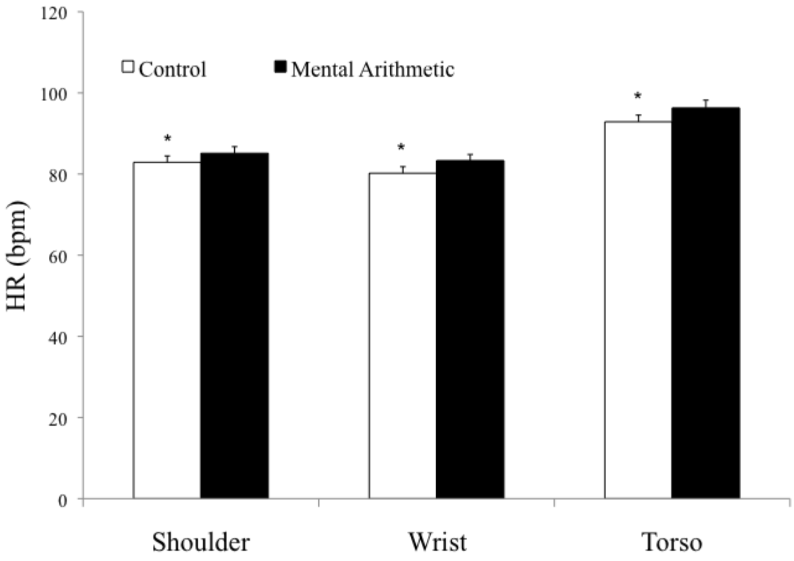


Figure 5. Main effect of MWL on average HR for the shoulder, wrist, and torso muscle groups. Error bars represent standard error. The symbol * indicates a significant difference between the Control and Mental Arithmetic conditions.

Performance measures

Motor performance

Force fluctuations during shoulder, torso, and wrist exertions were significantly influenced by PWL. Post-hoc analysis revealed that force fluctuations followed a U-shaped curve (Figure **6**), with 5% MVC resulting in the highest fluctuations, followed by 65% MVC, and then by 35% MVC, for shoulder and torso exertions. However, force fluctuations during wrist extension were highest at the 65% MVC compared to 5% and 35% MVC. MWL significantly increased force fluctuations by 24.6% during torso extension (p = 0.018), and an increase of 9.6%, trending toward significance, was observed during shoulder abduction (p = 0.052). For wrist extension tasks, adverse effects of MWL on force fluctuation were not observed.

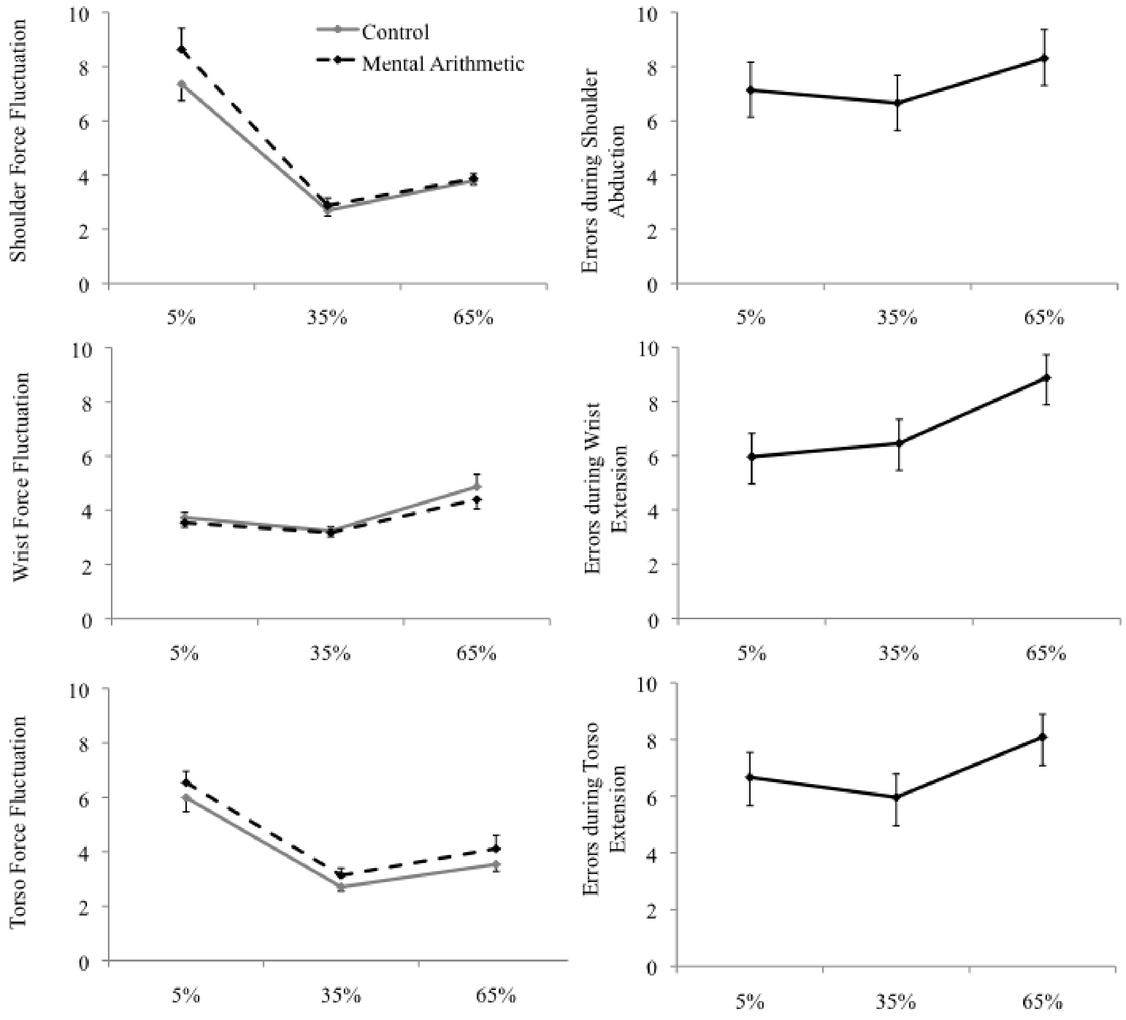


Figure 6. Influence of PWL and MWL on motor (force fluctuations) and mental task (errors) performance during shoulder abduction, and wrist and torso extension. PWL levels are percentages of MVCs (as described in the Methods). Error bars represent standard error.

Mental task performance

There was a significant main effect of physical demand on mental task performance, across all muscle groups (Figure **6**). Specifically, participants made more errors at 65% compared to 35% MVC during shoulder abduction (24.8% increase), and at 65% compared to 5% and 35% MVC during wrist (49 - 37.4% increase) and torso extension (21.2 – 35.7% increase). Although gender did not influence mental task performance during shoulder abduction (*p* = 0.11) and torso extension (*p* = 0.086), it had a main effect on wrist extension (*p* = 0.0398), with females making

59.4% more arithmetic errors compared to males. Type A tendencies did not influence mental task performance.

Subjective assessments

Ratings of perceived exertion

RPEs increased significantly with increases in physical exertion levels across all muscle groups (all $p < 0.0001$). The effect of MWL or gender was not significant, and no additional significant interactive effects were found.

NASA-TLX scores

A significant main effect of PWL (all $p < 0.01$) on all sub-scales and overall workload score was found across all muscle groups, with participants reporting higher scores with increasing physical levels. Presence of the mental arithmetic task elicited higher scores on all sub-scales and overall workload across all muscle groups (all $p < 0.0001$), except the Physical Demand sub-scale. A significant PWL and MWL interaction effect was found for the Effort sub-scale during wrist extension ($p < 0.0001$), and overall workload during wrist extension ($p < 0.0001$) and torso extension ($p = 0.0234$) with participants reporting greater perceived Effort and overall workload with the mental arithmetic task at 5% MVC compared to the other PWL conditions. Gender had a main effect on Performance, Effort, Frustration sub-scale scores, as well as overall workload score during shoulder abductions (all $p < 0.05$) and on Performance scores during wrist extension ($p = 0.0244$), with females reporting higher scores than males (higher performance scores indicate greater perception of failure).

Discussion

The current study aimed to determine whether additional mental demands interacted with varying levels of physical demand to affect physiological, performance, and perceptual measures. A secondary aim was to determine if any of these changes were dependent on the muscle group employed. The main findings of this study were (1) muscle activity across all muscle groups increased significantly in response to the levels of physical demands but decreased at high physical workload levels with the addition of a mental arithmetic task, (2) muscle oxygenation decreased significantly with increasing physical demands, but was not influenced by the mental task, (3) HR and HRV increased significantly with increasing physical demands, however only HR increased with the additional mental task, and (4) motor performance deteriorated under conditions of concurrent processing more so in the postural muscle groups when compared to the executive muscle group.

Physiological responses

As expected, increasing physical demands were associated with greater muscular activity and coactivity, along with higher metabolic consumption and increased cardiovascular responses. With regards to mental workload, additional mental demands decreased muscle activity and coactivity across all muscle groups. Previous studies that have evaluated the effects of cognitive stressors, such as mental arithmetic, choice reaction time tasks, and the Stroop color word test, have reported an increase in muscle activity at low-level static exertions (Laursen et al., 2002; Lundberg et al., 1994; Waersted, 2000; Waersted et al., 1991). This increase in muscle tension could be attributed to direct biomechanical changes (such as increased pacing, higher key strike forces, etc.) or structural interference (during the response phase) between the physical and mental tasks. Furthermore, these muscular responses to cognitive stressors were only evaluated during low physical exertions for prolonged duration. Experimental protocols employed in the current study did not allow for any undesired or unaccounted biomechanical changes, by instructing participants to maintain their force output within a tolerance band and by securing their posture. Unlike previous studies, no significant change in muscle activity for any of the muscle groups was found at lower levels of physical workload. However, compared to the work duration employed by previous studies, the current study was conducted for three minutes, with 90 seconds of cumulative work periods and 90 seconds of rest. Pilot work (Mehta & Agnew, in press) had previously indicated that 10 seconds of work task may not have been sufficient to evoke physiological responses to mental demands, thus it is possible that at low-level intermittent static work with a duration of three minutes, the effects of mental demand on muscle tension may not be comparable to what has been reported in existing literature. The current study employed three minutes of intermittent static work, determined from additional pilot testing, to avoid inducing any muscular fatigue due to the different levels of physical workload. Therefore, future work should consider the influence of task duration on responses to concurrent demands, as this might provide a more realistic approach to overall workload determination and evaluation.

At higher physical workload, it was found that participants were unable to generate the required muscle effort during concurrent processing across all muscle groups. Similar decreases in muscle activity, due to presence of cognitive stressors, have been reported at maximal voluntary shoulder exertions (Macdonell & Keir, 2005), at 40% MVC (Au & Keir, 2007), and exertions above 45% MVC in pilot work (Mehta & Agnew, in press). It is possible that at higher physical workload conditions, additional mental workload reduced available attentional resources that were needed to increase the drive to motor neurons to maintain the required force levels (Welford, 1973), resulting in reduced muscular output. In line with this theory, it is suggested that the dorsolateral prefrontal cortex may be responsible for the interference as it is involved in tasks related to working memory and response selection (Rowe et al., 2000) and has shown increased activity during isometric motor contractions (Dettmers et al., 1996).

Oxygen saturation was sensitive to changes in physical workload, with greater oxygen consumption observed at higher physical workload levels. Similar patterns of muscle oxygenation have been captured via near infra-red spectroscopy in different task conditions, such as sustained and intermittent contractions of the shoulder (Jensen et al., 2008), wrist (Heiden et al., 2005), and torso (Kell & Bhambhani, 2006). Few studies have investigated the effects of mental demands on muscle oxygenation; however the results have been inconclusive. Time pressure and precision demands have been found to influence oxygen consumption of the wrist muscle (extensor carpi radialis), but not the shoulder muscle (trapezius) (Heiden et al., 2005). It could be argued that the reduction in oxygen saturation may be attributed to higher work intensity rather than mental demands, as prior studies have shown associations between decreasing muscle oxygenation with increasing work pace (Bhambhani et al., 1999; Chuang et al., 2002). As the mental arithmetic task employed in the current study did not impose any structural interference with the physical task, it did not influence muscle oxygenation for any of the muscle groups. Similar results have been found when superimposed mental load, presented as the Stroop color word test, were not found to influence oxygen consumption of the trapezius during low-level repetitive work (Flodgren et al., 2009).

Cardiovascular responses, quantified using heart rate and heart rate variability, were found to be sensitive to changes in physical and mental workload. Heart rate has been shown to increase linearly with oxygen consumption under moderate physical exertions and to increase under high physical demands (Astrand & Rodahl, 1986). Similar effects of physical workload on heart rate were found in the current study, with average heart rate increasing with increasing physical workload during shoulder, wrist, and torso exertions. Although heart rate is a generally accepted cardiovascular indicator of physical workload, it was also influenced by additional mental workload in the current study. Similar increases in heart rate have been reported with concurrent tasks requiring physical and mental processing (Finsen et al., 2001; Wahlström et al., 2002) and with mental stress (Krantz et al., 2004; Lundberg et al., 2002). Additional mental workload did not have a differential effect on physical workload levels, evident by the absence of a significant interaction effect.

In comparison to heart rate, HRV (temporal and spectral components) is an indicator of mental workload (Kalsbeek & Ettema, 1963; Meshkati, 1988). In the current study, HRV was influenced by physical workload but was not affected by mental workload. Existing literature on the effect of heart rate variability on mental workload has shown conflicting results, with some studies reporting changes in heart rate variability (Hjortskov et al., 2004) whereas others observed no difference (Garde et al., 2002). It has been shown that HRV is influenced by changes in physical workload (Luft et al., 2009), and it could be possible that the effects of mental demand on HRV were masked by physical workload conditions. However, with additional mental demands, HRV was found to increase at 5% MVC during wrist extension and decrease at 65% MVC during torso extension compared to the control conditions. It is suggested that HRV is more reliable at higher compared to lower workload levels, as inter-beat intervals are constant over time at higher levels (Meshkati, 1988). Thus the inconsistencies found in HRV, which indicates an interaction between physical and mental workload, warrants further investigation.

Performance measures

The decrease in muscle activity and coactivity during conditions requiring both physical and mental processing may have led to the deterioration in motor performance, evident by increased force fluctuations during shoulder and torso exertions. Furthermore, no changes were observed in the co-contraction indices of the shoulder and torso, suggesting muscle recruitment did not change in an attempt to increase joint steadiness/stiffness. However, motor performance during wrist exertions was not influenced by additional mental demands despite a decrease in observed muscle activity. A possible explanation for this outcome may lie in the difference between motor units of the wrist muscles, which are functionally executive muscles, versus that of the shoulder and torso, which are functionally postural muscles. Shoulder and torso muscles are comprised of larger motor units compared to the wrist; thus these muscles may have recruited fewer motor units for a given force output, resulting in increased motor variability and impaired motor performance (Christou et al., 2003; Enoka et al., 2003). This was supported by the force fluctuation data from the current study, in that the overall force fluctuations observed during shoulder abduction and torso extension ranged from 2.8 – 8.6 % compared to 3.2 – 4.9% during wrist extension **(**Figure **6)**. According to the neuromotor noise theory proposed by Gemmert & Galen (1997), the signal-to-noise ratio of a neuromotor signal is the summed outcome of the recruitment of motor signals and the neuromotor activity due to concurrent cognitive processes. Thus, when coupled with additional neuromotor noise attributed to mental demands, it could be argued that the shoulder and torso exertions generated more pronounced effects on motor control impairment than the wrist exertions.

According to the Inverted U Hypothesis (Martens, 1974; Welford, 1973; Yerkes & Dodson, 1908), acute exercise intensity is associated with changes in arousal of the central nervous system that moderates cognitive performances, such that the optimal performance level corresponds to an intermediate arousal level. In line with this theory, mental arithmetic task performance in the current study roughly followed a U-shape curve, with a greater decrease in performance at the either end of the physical workload spectrum; a similar relationship to that observed for motor performance **(**Figure **6**). Particularly, highest force levels (65% MVC) resulted in a greater number of errors made compared to other force levels across all muscle groups, indicating maximum interference between the physical and the mental task at that level. Findings from previous studies examining the effects of high (60% MVC) levels of physical demands on mental task performance have reported a simultaneous decline of motor and mental task performance, similar to that found in the current study (Lorist et al., 2002; Zijdewind et al., 2006). At low levels of physical exertion, performance decrements occur due to insufficient arousal or a lack of motivation, which may induce boredom (Welford, 1973).

Subjective assessments

Ratings of perceived exertion increased with increasing physical demands but were not sensitive to changes in mental workload across all muscle groups. On the other hand, NASA-TLX sub-scales and overall workload scores were sensitive to changes in both physical and mental workload. Increasing physical workload elicited higher scores from all sub-scales and overall workload. Participants perceived conditions with mental arithmetic task to be more mentally demanding, rushed, effortful, and frustrating. Furthermore, they perceived that their performance deteriorated under conditions requiring both physical and mental processing and identified these conditions with higher overall workload. The Physical Demand sub-scale was not sensitive to changes with mental workload, irrespective of the muscle group employed. No interaction between physical and mental workload was found for any NASA-TLX scores except the Effort sub-scale and overall workload during wrist extension and overall workload during torso extension. Participants perceived greater effort and overall workload to exert 5% MVC wrist/torso extension while concurrently performing mental arithmetic. The NASA-TLX tool has been widely employed for assessing tasks requiring mental processing (Hart & Staveland, 1988), however the findings from the current study emphasizes its sensitivity to tasks with combined physical and mental demands. Gender was found to influence some NASA-TLX scores, but had no effect on Borg CR10 ratings. As the physical workload levels were normalized to each individual's maximum strength, gender differences in perceived exertion ratings were not expected. In general, females perceived shoulder abductions to be more effortful, frustrating, and resulting in a greater overall workload than males. Furthermore, perception on performance deteriorated more for females than males during shoulder and wrist exertions.

Limitations and future directions

This study has several limitations that should be acknowledged. First, the study manipulated mental workload at two levels, absence and presence of a mental arithmetic task. However, the primary goal of this study was to determine if varying levels of physical workload will interact with additional cognitive processing. Furthermore, mental arithmetic was employed in this study as it (1) offered minimal interference with the physical task, (2) has been shown to induce psychological stress and evoke specific physiological responses (Allen & Crowell, 1989; Schleifer et al., 2008), and (3) required cognitive processing that is representative of mental demands placed on workers at their daily jobs. Future work should build on the results from the current study, by evaluating the effects of other cognitive and psychosocial stressors, both laboratory-based and those representative of occupational tasks, at multiple levels.

Second, although industrial work postures are characterized by simultaneous activation of multiple muscles, the study employed physical tasks that required separate exertions of the shoulder, wrist, and torso. Since the secondary goal of this study was to determine if concurrent demands have differential effects on different muscle groups, separate exertions for each muscle group were considered in isolation to minimize inter-individual variability in muscle recruitment strategies. Results from this study pertaining to muscle-specific responses to concurrent demands should be used as a basis to further assess the effects of concurrent demands during actual industrial tasks employing multiple muscles. Additionally, participants performed the physical and mental task for a relatively short duration compared to that commonly experienced by workers. However, this duration was employed to avoid inducing any muscular fatigue due to different levels of physical exertion. Therefore, further investigation is needed to determine interactive effects of concurrent demands for durations representative of occupational tasks.

Finally, the study focused on a young age group (age range from 18-25 years). The Bureau of Labor Statistics (2006) projected that by 2016, about 44% of the U.S. workforce will be comprised of workers 45 years or older, thus future research is warranted to investigate age-related effects of concurrent demands on physiological and performance outcomes.

Practical implications

The results of this study have several practical implications. Higher physical workload levels were found to be more sensitive to interference with mental demands, which resulted in adverse physiological responses. Thus, for tasks requiring higher cognitive processing, associated physical demands should be reduced such that attentional resource allocation is optimized. Additional mental demands negatively affected physical and mental task performance at high and low levels of physical workload, and this relationship was prominent for postural muscles compared to executive muscles. Engineering or administrative controls can be employed to revise work task parameters (such as force levels, duration, and rest allowances) and tool or workstation design (such as angles/postures, limb support) to alleviate performance decrements due to physical workload. Additionally, task design principles, such as top-down processing, redundant coding, or usage of affordances, can be adopted in product/task design to support pre-attention that could reduce cognitive processing loads associated with the task (Norman, 1999; Wickens & Hollands, 2000).

Conclusions

Workplace tasks, such as jobs performed by healthcare workers, assembly line workers, and computer operators, have become more multidimensional in the recent years; with workers experiencing combined physical and mental demands, yet their contributions to the development of musculoskeletal injuries is not clearly understood. Results from this study highlight differential effects of mental demands on physical demands, suggesting that certain force levels are more susceptible to physiological reactivity (as observed by decreased muscle activity and increased cardiovascular load) and performance decrements than others. Additionally, these interactions are muscle-dependent, with postural muscles indicating a greater propensity to interference due to concurrent demands than executive muscles. It is therefore important to consider job parameters, such as type and levels of task demands and muscle employed, during task design to minimize the overall demands placed on workers. Future work should build on these results by addressing different types of psychosocial demands prevalent in the workplace and employing other work parameters, such as task duration and postures utilizing multiple muscles, in order to generalize the findings to occupationally relevant tasks and/or environments. It is envisioned that the results from this study will facilitate the development of ergonomic interventions in the workplace, such as overall workload determination and tool and workstation design, that may help reduce risk of workplace injuries as well as avoid worker performance degradation. Furthermore, applications of these results may aide in the development of ergonomics tools that will incorporate concurrent assessment of physical and mental workload in the workplace.

Chapter 3: Exertion-dependent effects of physical and mental workload on physiological outcomes and task performance

Abstract

Background: Static work is considered an occupational risk factor in the development of injuries, thus there is an emphasis on employing dynamic exertions to work tasks. With workers experiencing concurrent physical and mental demands in their daily jobs, it is unclear whether these exertion types affect overall task demands differentially.

Objectives: The aim of this study was to compare exertion-dependent physiological responses due to concurrent physical and mental workload during intermittent shoulder exertion.

Methods: Twelve young participants, balanced by gender, performed intermittent static and dynamic work for three minutes at three levels of physical workload (low, moderate, and high) in the absence and presence of a mental arithmetic task. Study measures included muscle activity, muscle oxygenation, task performance measures (motor performance and mental arithmetic task performance), and subjective responses.

Results: Static exertions and higher physical demands adversely affected physiological responses, performance measures, and were associated with greater perception of exertion and workload. Additional mental demands negatively affected muscle activity, mental task performance, and subjective measures. Moreover, these results were more pronounced during static exertions at high physical demand levels.

Conclusions: Results indicated that certain job parameters (static exertions and high physical demands) are more susceptible to interference with mental demands than others (dynamic exertions and low demands). As such, it is important to consider the interaction of work parameters, specifically physical demand levels and exertion type, when assessing overall demands placed on workers during concurrent physical and mental work.

Keywords: static, dynamic, physical workload, mental workload, performance

Introduction

In 2008, upper extremity disorders alone accounted for more than 318,250 cases of nonfatal injuries and illnesses (BLS, 2008). Injuries to the shoulder and wrist resulted in a median of 18 and 16 days away from work, respectively. Also labeled cumulative trauma disorder, repetitive strain injury, and work-related upper extremity disorder (WRUED), the total cost for these disorders in the United States has been estimated to range from $563 million (Webster & Snook, 1994) to $6.5 billion in 1989 (Silverstein et al., 1998). Task-related factors such as repetitiveness and forceful exertions, and the combination of both, have shown the strongest association to WRUEDs (Kilbom, 1994), with repetitive motion responsible for injuries with the highest median days away from work (18 days) (BLS, 2008). Awkward postures, low-level static work, prolonged duration, and insufficient recovery can also exacerbate the risk of shoulder injury (Hagg, 1991; Malchaire et al., 2001).

In addition to the physical risk factors, work-related psychosocial factors, such as intensified workload, job control and social support, have been consistently associated with WRUEDs (Bernard, 1997; NRC, 2001). Psychosocial risk factors can influence musculoskeletal pain by varying the biomechanical demands (Bongers et al., 1993), increasing awareness of pain symptoms (Sauter & Swanson, 1996), or adversely affecting physiological attempts at recovery (Melin & Lundberg, 1997). Evidence of these mechanisms, which have been previously reported in several laboratory experiments, include increased muscle tension (Lundberg et al., 1999; Waersted & Westgaard, 1996), altered joint kinematics (Faucett & Rempel, 1994), interference with blood flow and energy metabolism (reviewed in Warren, 2001), and changes in blood catecholamine levels (Lundberg, 2002). Although most of the research investigating physiological reactivity of mental demands and/or stress has focused on low-level static exertions (Laursen et al., 2002; Lundberg et al., 1994; Waersted, 2000; Waersted et al., 1991), recent studies have demonstrated the differential effects of mental demand on varying force levels during static work (Mehta & Agnew, in press, Chapter 2). Findings from these studies suggest that additional cognitive demands reduce generation of muscular effort at higher force levels, and concomitantly cause greater impairment in motor coordination. Similar decreases in shoulder muscle activity have been found during static shoulder abduction at 40% maximum voluntary contraction (Au & Keir, 2007) and peak force generation (Macdonell & Keir, 2005).

Repetitive work is common in many industrial tasks, such as computer-based and assembly line work (Carter & Banister, 1994). These tasks may be comprised of either static or dynamic exertions, or a combination of both during continuous or intermittent work. Low-level static efforts are one of the major predictors of musculoskeletal disorders (Bernard, 1997; Sjogaard & Jensen, 2006), thus there is a greater emphasis on employing dynamic exertions to occupational tasks to reduce risk of injuries (Takala, 2002). However, dynamic exertions result in greater energy consumption compared to equivalent static exertions for low force levels (Bridges et al., 1991; Vedsted et al., 2006), resulting in larger muscular load. Even so, sustained static exertions can cause greater reductions in muscle oxygenation due to the absence of the rhythmic muscle contraction that facilitates muscle perfusion in dynamic contractions (Heiden et al., 2005; Jensen et al., 1999). These large reductions in muscle oxygenation levels have been suggested to contribute to the development of work-related musculoskeletal injuries (Carayon et al., 1999; Galen et al., 2002).

Additional task demands, such as mental processing or increased pacing, may exacerbate the existing risk of injuries on workers during static and dynamic exertions, by evoking specific physiological responses that may result in impairment of muscular functions. Specifically, these responses include alteration of muscle contractility and reduced muscle spindle sensitivity (Passatore & Roatta, 2003). Changes in spindle sensitivity during limb movement detrimentally affect proprioceptive information flow and may alter motor control by causing joint perturbations

(Johansson et al., 2003). This could also result in increased muscular co-contraction, leading to sustained muscle activity, to stabilize perturbed joints (Waersted, 2000). Research investigating the effects of mental demands on muscular responses has largely focused on low-level static exertions (Lundberg et al., 2002; Lundberg et al., 1994). Few studies have reported changes in physiological responses during dynamic exertions (Galen et al., 2002; van Loon et al., 2001); it is however unclear if one exertion type might be more susceptible to mental stress than the other at higher force levels. The neuromotor noise theory hypothesizes that the signal-to-noise ratio of the neuromotor signal comprises of neuromotor activity from motor unit recruitment and additional cognitive processes (Gemmert & Galen, 1997). Since human movement is inherently noisy, it is speculated that the overall outcome during dynamic exertions might result in greater deterioration of the signal-to-noise levels compared to static exertions. When coupled with additional neuromotor noise attributed to additional mental demands, dynamic exertions may lead to greater muscle stiffness through increased co-contractions to filter excessive noise, and may lead to greater impairment of muscular functions compared to static exertions.

The aim of this study was to compare exertion-dependent physiological responses due to concurrent physical and mental workload during intermittent shoulder exertion. Physiological responses, motor and mental task performance, and subjective assessment of perceived exertions and workload were measured under conditions of intermittent static and dynamic shoulder abduction at different physical workload levels, in the absence and presence of additional mental workload. To this end, two hypotheses were proposed: (1) changes in physiological responses due to concurrent physical and mental workload will be dependent on the type of exertion; and (2) these exertion-specific changes will be dependent on physical workload levels.

Methods

Experimental Design

A 2 (exertion type) x 3 (physical workload) x 2 (mental workload) full factorial repeated measures design was utilized to evaluate changes in physiological responses during intermittent shoulder abduction. Exertion type included intermittent static and dynamic exertions; physical workload (PWL) was induced as percent MVC of each subject at three force levels: low (15% MVC), moderate (30% MVC), and high (50% MVC), and mental workload (MWL) was presented at two levels: absence and presence of a mental arithmetic task. Each participant underwent two experimental sessions; each experimental session focused on one exertion type to minimize equipment setup time.

Participants

A total of twelve participants, balanced by gender, were recruited from the local community, whose mean (SD) age, stature, and body mass were 22.11 (1.7) years, 1.57 (0.57) m, and 68.39 (12.0) kg, respectively. Participants were limited to right-handed individuals with no self-reported injuries, illnesses, or musculoskeletal disorders within the past year. Informed consent, using procedures approved by the Virginia Tech Institutional Review Board (**Appendix B**), was obtained prior to the experiment.

Procedures

Participants attended one preliminary session and two experimental sessions, with at least two days in between to avoid any fatigue or carryover effects. In order to avoid any potential learning or order effects, presentation of the two experimental sessions were counterbalanced and a balanced Latin Square design was employed within each session to counterbalance the six treatment conditions.

Preliminary session

At the preliminary session, participants completed a student version of the Jenkins Activity Survey to quantify and subsequently account for Type A tendencies amongst the participant pool (Jenkins et al., 1979; Yarnold & Bryant, 1994). They were familiarized with the experimental task, i.e., both the physical task (intermittent static and dynamic shoulder abduction) and the mental arithmetic task. Once familiarized, participants performed a series of static and dynamic MVCs (Nm) to determine the levels of PWL used during the experimental sessions. They were seated in a dynamometer (Biodex™ System 3 Pro Medical System, Shirley, New York, USA), comfortably secured at the shoulder and waist in a seated position. Static MVCs were obtained by instructing participants to maximally abduct their arm at 45° against a padded dynamometer arm fixture, keeping the other arm resting at the side. To obtain dynamic MVCs, the dynamometer was activated in the isokinetic mode, with a set speed of 20°/s, and participants were instructed to maximally abduct their arm, from arm at side to arm horizontal (at 90°) against the dynamometer arm fixture. A minimum of three static and dynamic MVCs were performed, with two minutes rest given between each. The maximum torque value of three MVCs for each exertion was used to determine the PWL levels for that exertion type. The MVCs collected were corrected for gravitational effects acting on the limb and the Biodex™ apparatus.

Experimental sessions

Participants performed sufficient warm-up exercises at the beginning of each experimental session before being instrumented with electromyography (EMG) electrodes (Measurement Systems Inc., Ann Arbor, MI, USA) and a near-infrared spectrometer (NIRS) probe (OxiplexTS, ISS, Champaign, IL). EMG signals were collected using 10 mm, rectangular Ag/AgCl pre-gelled bipolar electrodes from the middle deltoid, as it has been shown to play a predominant role in shoulder abduction (Perotto, 1994; Yassierli & Nussbaum, 2007), and supporting co-contractors, such as the anterior and posterior deltoid, upper trapezius, and latissimus dorsi. Muscle sites on each subject were shaved and cleansed with alcohol to reduce skin resistance, and electrodes were placed on the muscle sites according to clinical procedures (Perotto, 1994). The NIRS probe was placed on the belly of the middle deltoid, aligned in the direction of muscle fiber. A 20-minute stabilization period was provided after electrode and probe placements, following which a quiet trial and muscle-specific MVCs were obtained across several standardized postures assumed to elicit maximal strength output of each muscle.

Experimental task conditions: Similar to the preliminary session, participants were seated and comfortably strapped in the dynamometer. Depending on the exertion type, participants were instructed to perform intermittent static or dynamic exertions, presented at three levels of PWL levels in the absence and presence of the mental arithmetic task. The task comprised of a series of work and rest cycles of 5 seconds each, for a duration of 3 minutes. For the intermittent static task, participants were strapped to the dynamometer arm fixture, positioned at 45°, and they were asked to abduct their shoulder against the fixture. Visual feedback was presented on a computer screen placed at eye height as a series of square waves displaying work and rest periods, thereby visually controlling the duration of the work-rest cycle **(**Figure **7)**. For each control condition (i.e., no mental arithmetic task), at 15%, 30%, and 50% of the static MVC, participants were instructed to maintain their exertion levels within ±5% of the target torque values during the work phase.

For the intermittent dynamic task, participants were strapped to the dynamometer arm fixture, and from “arm at side” they were instructed to abduct their shoulder against the padded arm to “arm horizontal” (at 90°). The dynamometer was activated in the isotonic mode, providing resistance equivalent to PWL levels. Participants were provided a visual feedback of the dynamometer arm position from 0° to 90°, on a computer screen, as a series of triangular waves displaying work and rest periods **(**Figure **7)**. The work period included the concentric phase of the arm abduction, and participants were asked to passively return to "arm at side" position at the end of each work period. PWL conditions were presented by manipulating the resistance offered by the dynamometer arm, along with external weights if needed, at 15%, 30%, and 50% of the dynamic MVC, and participants were asked to accurately track their position with respect to the feedback. Participants were given adequate practice at the preliminary session and at the beginning of each experimental session, at all PWL levels, to familiarize themselves with the task.

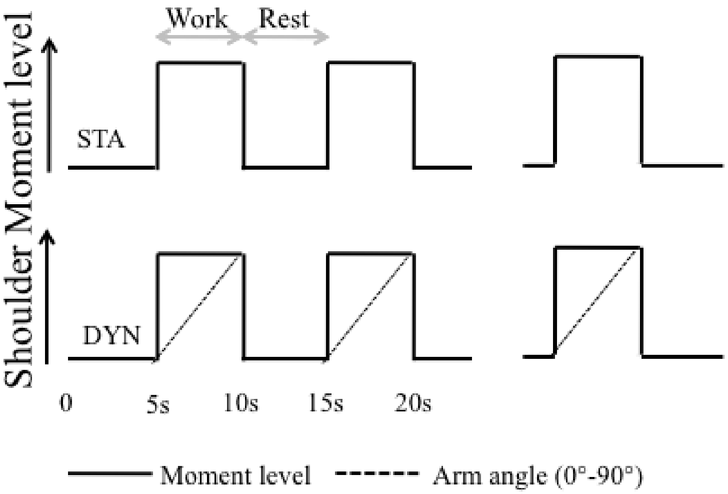


Figure 7. Illustration of intermittent static (STA) and dynamic (DYN) exertions.

For the concurrent task conditions, participants were asked to concurrently perform the mental arithmetic task and the physical task for three minutes. At every rest period, participants were verbally presented with a two-digit number (from 11-49) and a one-digit number (2-9) and were instructed to multiply these numbers and verbally provide an answer during or by the end of the following work period. Participants were encouraged to provide accurate answers while successfully maintaining the required force/position, and performance on the mental task was recorded. To help avoid any fatigue carryover effects, a 6-minute rest break (minimum) was provided after each treatment condition.

Measures

Physiological measures

Electromyography: Raw EMG signals of the trials, sampled at 1024 Hz, were corrected for signal bias (using a quiet EMG trial), band-pass filtered (20-450 Hz), full-wave rectified and subsequently low pass filtered (dual pass, 4th order Butterworth filter with effective cutoff frequency of 3 Hz), using a custom program developed in LabVIEW (National Instruments, TX, USA). EMG signals from each muscle were normalized with respect to their maximum value (which were processed similarly). EMG amplitudes for all muscles were obtained as an average of the middle 3-second window of each 5-second work period for each treatment condition. Further, co-contraction indices (CCI) of the shoulder was calculated as the ratio of the activation of latissimus dorsi with respect to the combined activation of the three deltoids and the upper trapezius, multiplied by the sum of the activity of all muscles (Rudolph et al., 2001). Activation of the agonist shoulder muscles, agonist EMG, was determined as the summation of all agonist muscles (three deltoids and upper trapezius).

Muscle oxygenation: Near-infrared spectroscopy (NIRS) has been employed to non-invasively monitor local muscle oxygenation to quantify physical workload (Chuang et al., 2002; McGorry et al., 2009) and compare oxygen consumption during static and dynamic work (Vedsted et al., 2006). Oxygen saturation data was collected with a sampling frequency of 2 Hz. Before probe placement, the system was calibrated according to the manufacturer’s instructions. The absolute value of percent saturation was recorded continuously for the whole trial. The middle 3-second data of each work period was utilized and averaged across each treatment condition to obtain mean oxygen saturation levels.

Performance measures

Motor performance was assessed by measuring steadiness in force generation (Christou & Carlton, 2002; Enoka et al., 2003). Torque output data from the dynamometer were collected for the entire duration of each treatment condition, sampled at 1024 Hz, and low pass filtered at 15 Hz. Utilizing the middle 3-second window of each work period, force fluctuations were quantified as the coefficient of variance of the exerted force (calculated as standard deviation/mean force) and averaged across each treatment condition (Enoka et al., 2003; Ranganathan et al., 2001). Performance on the mental arithmetic task was recorded (i.e., the number of incorrect answers/no answers), and quantified for each treatment condition.

Subjective measures

The Borg CR10 scale was used to obtain Ratings of Perceived Exertion (RPEs) of the shoulder at the end of every treatment condition (Borg, 1990) (**Appendix D**). The anchors ranged from “0, nothing at all”, to “10, extremely strong (almost max)”. Additionally, the NASA Task Load Index (NASA-TLX) was employed to obtain participants’ perception of workload on six scales: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration (Hart & Staveland, 1988). Participants were asked to rate the levels of these sub-scales between 1 (Low) and 20 (High) after the completion of each treatment condition (**Appendix E**). Weighted ratings for each sub-scale, obtained from 15 pair-wise comparisons, were calculated by multiplying each rating by the weight given to that sub-scale by the participant. The individual sub-scale measures and an overall workload score (scored from 0 to 100), calculated as (sum of the weighted ratings of each sub-scale/15), were used to compare between the different treatment conditions.

Analysis

Separate three-way repeated measures ANOVAs were conducted to determine main and interaction effects of exertion type, physical and mental workload on the physiological, performance, and subjective measures. Furthermore, a two-way ANOVA was conducted to test for main and interactive effects of exertion type and physical demand on mental task performance. For all analyses, gender and order of exposure were included as blocking variables. Order had no effect on any dependent measure (all $p > 0.05$) and was thus removed from the final statistical model. To test inter-item reliability on the items in the personality questionnaire pertaining to Type A tendencies and NASA-TLX responses, standardized Cronbach's alpha values were determined. For all items in the Jenkins Activity Survey, Cronbach's alphas ranged from 0.33 to 0.59 (entire set = 0.45), indicating that Type A scores had low reliability (Nunnally, 1978). Thus, further analyses of Type A scores were not conducted. Inter-item reliability of the NASA-TLX scores ranged from 0.85 to 0.91 (entire set = 0.89). As no substantial violations of parametric assumptions were evident, parametric analyses were conducted using JMP 8.0 (SAS Institute Inc., USA). Where required, post-hoc comparisons were conducted using Tukey's Honestly Significant Difference test. Statistical significance was determined when $p < 0.05$. All summary values are presented as means (SD).

Results

Significant main and interaction effects of exertion type, PWL, and MWL on the physiological, performance, and subjective measures are summarized in Table **2**. Gender did not influence any dependent measures (all $p > 0.05$).

Table 2. Summary of ANOVA results (p-values) for the effects of exertion type (E), PWL, and MWL on physiological, performance, and subjective measures. The symbol * indicates a significant effect ($p < 0.05$).

Measures		**E**	**PWL**	**MWL**	**E x PWL**	**E x MWL**	**PWL x MWL**	**E x PWL x MWL**
Mean EMG		0.917	<0.0001*	0.128	0.055	0.348	0.064	0.126
Agonist EMG		<0.0001*	<0.0001*	0.003*	<0.0001*	0.055	0.008*	0.01*
CCI		0.0024*	<0.0001*	0.828	<0.0001*	0.498	0.668	0.981
Oxygen saturation		0.77	<0.0001*	0.767	0.002*	0.36	0.083	0.502
Motor performance		0.029*	0.003*	0.608	<0.0001*	0.709	0.974	0.933
Mental task performance		0.061	<0.0001*	-	0.172	-	-	-
RPE		0.6542	<0.0001*	0.7293	0.0031*	0.7293	0.4856	0.2711
NASA TLX	MD	0.4264	0.0988	<0.0001*	0.8287	0.4558	0.9418	0.4225
	PD	0.0001*	<0.0001*	0.9057	0.0449*	0.8589	0.8046	0.8786
	TD	0.0388*	<0.0001*	<0.0001*	0.0649	0.0262*	0.0649	0.1321
	EF	0.0036*	<0.0001*	<0.0001*	0.0912	0.0143*	<0.0001*	0.0314*
	PF	0.0014*	0.0032*	<0.0001*	0.1202	0.0529	0.0077*	0.3866
	FR	0.2245	0.0001*	<0.0001*	0.0124*	0.0012*	0.0109*	0.5473
	OWL	<0.0001*	<0.0001*	<0.0001*	0.0018*	0.0113*	<0.0001*	0.2897

Note: MD: Mental Demand, PD: Physical Demand, TD: Temporal Demand, EF: Effort, PF: Performance, FR: Frustration, and OWL: Overall Workload.

Physiological responses

Electromyography

A significant main effect of PWL was observed for all EMG measures (mean EMG, agonist EMG, and CCI), with higher physical demands resulting in increased muscle activity and coactivity (all $p < 0.0001$). Additionally, exertion type significantly affected agonist EMG ($p < 0.0001$) and CCI ($p = 0.0024$), with static exertions causing greater coactivity than dynamic exertions. However, these main effects were driven by significant interaction effects of exertion type x PWL (both $p < 0.0001$). Compared to dynamic exertions, agonist EMG and CCI increased by 67% and 116% respectively at 50% MVC during static exertions. Although not significant, a similar borderline interaction effect was observed for mean EMG ($p = 0.055$).

MWL significantly reduced agonist EMG (*p* = 0.003) when compared to the control (104.43 (61.49) % MVC vs. 111.03 (66.77)% MVC). Although no evident trend was found for CCI (*p* = 0.828), mean EMG decreased by 4% (*p* = 0.128) in concurrent demand conditions compared to the control. A significant interaction effect of PWL x MWL was found on agonist EMG (*p* = 0.008), with agonist EMG decreasing by 7% due to MWL at moderate and high PWL levels (30% and 50% MVC respectively). No such differences were observed at 15% MVC. Mean EMG also followed a similar trend, although not significant (*p* = 0.064), that indicated a greater decrease in mean EMG induced by the mental arithmetic task at higher PWL levels. A borderline interaction effect of exertion type x MWL was found on agonist EMG (*p* = 0.055) that implied a greater decrease in coactivity due to MWL during static compared to dynamic exertions. A significant second-order interaction between exertion type x PWL x MWL (*p* = 0.01), further confirmed this trend, with a greater decrease in agonist EMG found in concurrent task conditions compared to the control for static exertions than dynamic exertions. However, this interaction was only significant at 50% MVC (Figure **8**).

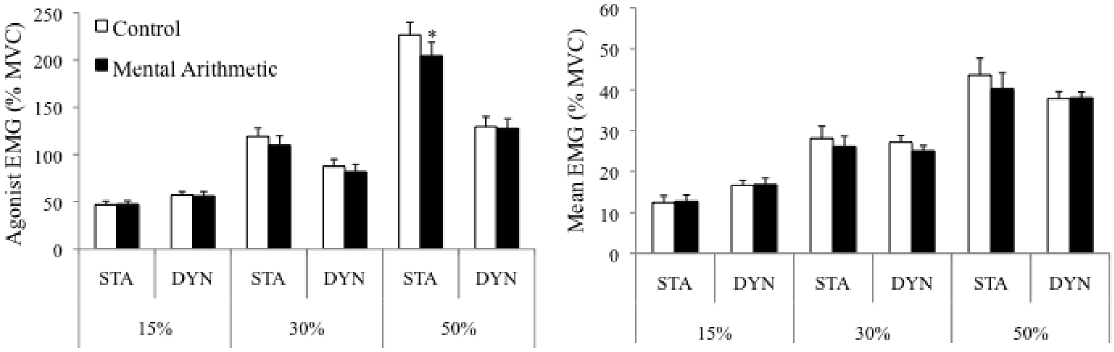


Figure 8. Interactive effects of exertion type, PWL, and MWL on agonist EMG (left) and trends observed on mean EMG (right) during intermittent static (STA) and dynamic (DYN) shoulder abduction. Error bars represent standard error. The symbol * indicates a significant difference between the Control and Mental Arithmetic conditions.

Muscle oxygenation

Increasing PWL levels resulted in greater reductions in oxygen saturation ($p < 0.0001$). A significant interaction effect of exertion type x PWL was found ($p = 0.002$), with static exertions (63.88 (6.9)) resulting in greater reduction on oxygen saturation than dynamic exertions (65.96 (4.1)) at 30% MVC (Figure **9**). No significant main effects of MWL ($p = 0.767$) or any first- or second-order interaction effects of exertion type x MWL ($p = 0.36$) or exertion type x PWL x MWL ($p = 0.502$) were found on oxygen saturation. Although failing to reach significance, an interaction effect of PWL x MWL was observed ($p = 0.083$) that indicated a greater reduction in oxygen saturation during concurrent demand conditions compared to the control at 50% MVC.

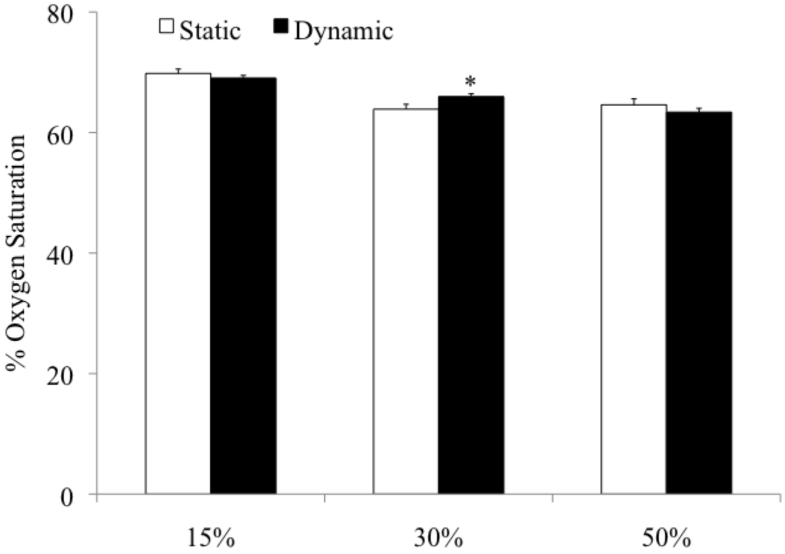


Figure 9. Interactive effects of exertion type and PWL on oxygen saturation. Error bars represent standard error. The symbol * indicates a significant difference between the static and dynamic conditions.

Performance measures

Motor performance

Significant main effects of PWL ($p = 0.003$) and exertion type ($p = 0.029$) were found on force fluctuation. Higher fluctuations were observed at 15% MVC (5.47 (4.89)) compared to 30%

(4.42 (2.46)) and 50% MVC (4.73 (3.18)) and for dynamic exertions (6.04 (4.6)) compared to static exertions (3.67 (1.65)). A significant interaction of exertion type x PWL was observed ($p < 0.0001$), with higher fluctuations observed at 15% MVC during dynamic exertions than in any other condition. There were no significant main effect of MWL, or any first- or second-order interaction effects with exertion type and PWL were found on force fluctuations.

Mental task performance

A significant main effect of PWL ($p < 0.0001$) was found on mental task performance. Higher errors were observed at 15% MVC (12.79 (4.52)) compared to 30% (11.08 (4.62)) and 50% MVC (11.21 (4.84)). Although not significant, a borderline main effect of exertion type was observed ($p = 0.061$) on mental task performance, with higher errors made during static exertions than during dynamic exertions (Figure **10**). No significant interaction effect of exertion type and PWL ($p = 0.172$) was found on mental task performance.

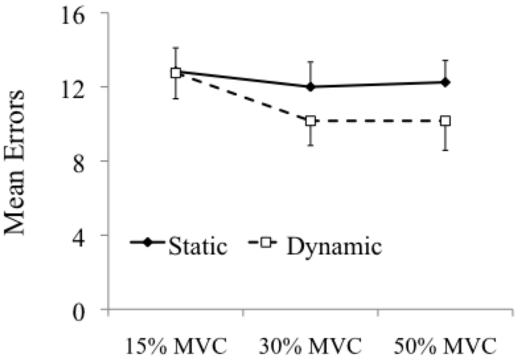


Figure 10. Mental task performance during intermittent static and dynamic exertions. Error bars represent standard error.

Subjective measures

Ratings of perceived exertion

Ratings of perceived exertion increased significantly with increases in PWL levels ($p < 0.0001$). A significant interaction effect of exertion type and PWL was found on RPE, with participants reporting greater perceived exertion at 50% MVC for static (5.97 (3.03)) compared to dynamic exertions (4.97 (2.24)). The effect of MWL was not significant, and no additional significant interactive effects were found.

NASA-TLX scores

A significant main effect of exertion type was found on four NASA-TLX six sub-scales, including Physical Demand, Temporal Demand, Effort, Performance, and the overall workload score (refer Table **2** for *p*-values). PWL was found to significantly affect the Frustration sub-scale, in addition to the above measures. In general, participants reported higher scores during static exertions than dynamic exertions, and at 50% MVC compared to 30% and 15% MVC. Note that higher scores indicate increased perception of mental, physical, and temporal demand, higher perceived effort and frustration, and greater perception of failure. Additionally, a significant interaction effect of exertion type x PWL was found on the Physical Demand and Frustration sub-scale and the overall workload score, with participants reporting higher scores at 50% MVC during static exertions than during dynamic exertions.

MWL was found to significantly increase scores on all sub-scales and overall workload, except the Physical Demand sub-scale. A significant interaction effect of exertion type x MWL was found on Temporal Demand, Effort, and Frustration sub-scale, as well as the overall workload score. Although participants reported higher scores in the concurrent demand conditions compared to the control, they reported higher scores when performing static exertions than dynamic exertions in the control condition. An interaction effect of PWL x MWL was found significant on the Performance, Effort, and Frustration sub-scales and overall workload, with higher scores reported at 15% MVC in the presence of mental arithmetic compared to other conditions (Figure **11**). Finally, a significant three-way interaction effect of exertion type x PWL x MWL was found on the Effort sub-scale, with participants reporting greater effort at 50% MVC during static exertions than during dynamic exertions. However, this interaction was only significant during the control conditions.

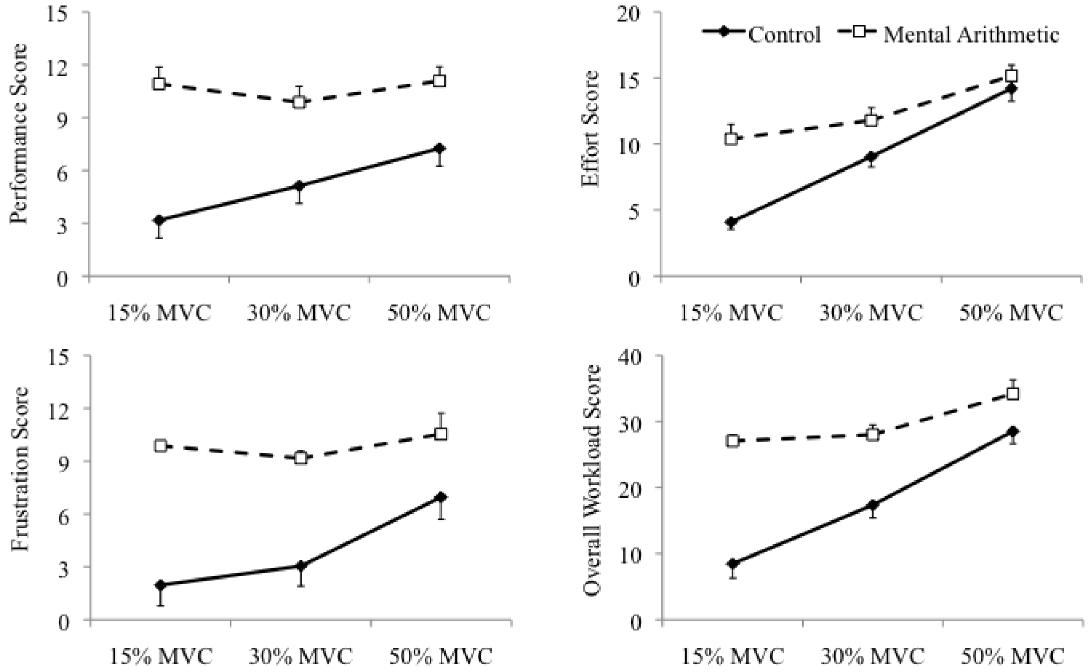


Figure 11. Influence of PWL and MWL on Performance, Effort, and Frustration sub-scales and overall workload score. Error bars represent standard error.

Discussion

The present work addressed differential effects of exertion type on concurrent physical and mental demands during intermittent static and dynamic shoulder abduction. In general, exertion type and physical demand were found to influence physiological responses (i.e., EMG and oxygenation measures), motor and mental task performance, and most subjective measures. Additional mental demands significantly affected some EMG measures and NASA-TLX scores; more importantly, the relationship was influenced by exertion type and physical demand. These findings supported our primary hypothesis that mental demand caused stronger interferences during static exertions at higher intensities resulting in reduced muscular output and impaired mental performance.

Exertion type and physical demand

Higher physical demands and static exertions were associated with increased muscle activity and coactivity; these relationships were more pronounced at higher force levels. Although not significant, EMG activity during low-level dynamic exertions (at 15% MVC) increased by 36.6% when compared to static exertions. Previous work investigating effects of exertion type reported similar increases in EMG activity during dynamic exertions when compared to static exertions at 10-20% MVC (Vedsted et al., 2006). Although larger reduction in oxygen saturation was observed during dynamic exertions at 15% MVC, it wasn't significantly different from static exertions. However, at 30% MVC, oxygen consumption increased in static compared to dynamic conditions, with equivalent muscular effort. This may be explained, at least in part, by a generation of higher intramuscular pressure that may have resulted in impeded blood flow during intermittent static contractions (Sjogaard et al., 2004; Zhang et al., 2004). At 50% MVC, mean EMG was similar across both exertion type, however agonist EMG (a summed measure of EMG from all agonist muscles) was considerably higher during static compared to dynamic exertions.

Muscle co-contraction (CCI) was lower during dynamic than during static exertions, specifically at higher physical demand levels. This may have negatively affected joint steadiness, resulting in the greater decrements of motor performance (increase in force fluctuations) that were documented during dynamic exertions. Subjective assessment of exertion and workload followed physiological measures closely by capturing the interactive effect of exertion type x physical demand on Borg CR10 ratings and some NASA-TLX scores. In general, higher physical levels during static exertions were perceived to be more physically demanding, effortful, and frustrating and were associated with higher overall workload levels compared to dynamic exertions. Trends of the temporal demand scores suggested that participants perceived greater time pressure (perception of being rushed) performing static exertions than dynamic exertions at high physical demand levels (p = 0.0649).

Differential effects of exertion type on concurrent demands

With regards to additional mental demand, a decrease in EMG activity was observed, however both physical demand levels and exertion type influenced this relationship. As seen in Figure **8**, there was no change in EMG (mean or agonist) at 15% MVC, but a significant EMG decrease was observed at 50% MVC due to the mental arithmetic task. Previous work that addressed high force levels found similar decreases during shoulder abduction due to the Stroop color word test (Au & Keir, 2007; Macdonell & Keir, 2005) and mental arithmetic (Mehta & Agnew, in press, Chapter 2). In the current study, the task required participants to maintain their force levels at a target level while performing a mental arithmetic task. It could be argued that at low-level exertions, participants were able to maintain their exertion, with the biofeedback preventing them to overshoot their target, while mentally processing the arithmetic questions. However, to maintain exertions at higher physical demand levels and to perform mental arithmetic, a lack of available attentional resources caused a decrease in muscular effort (Welford, 1973), resulting in a decline of EMG activity and coactivity.

Interestingly, the interactive effects of physical and mental demands on EMG activity were further influenced by exertion type. When compared to control conditions, a greater decrease in agonist EMG activity was found in concurrent demand conditions during static exertions at 50% MVC than during dynamic exertions (9.7% vs. 1.5%, respectively). Although it could be argued that an agonist EMG measure may not offer a precise measurement of muscle activity for a given force level, it provides information regarding the collective activation of muscles around a joint. A similar trend observed in mean EMG activity of middle deltoid (prime mover during shoulder abduction) at 50% MVC (Figure **8**) further validates the differential effect of exertion type on concurrent demands.

Existing literature focusing on mental task performance have used dual task paradigms to evaluate resource allocation strategies and attentional demands by assessing changes in performance (Lorist et al., 2002; Ryu & Myung, 2005; Zijdewind et al., 2006). The primary objective of employing mental arithmetic task in this study was to manipulate mental workload (a study variable), and a secondary purpose was to quantify the amount of interference in attentional resource allocation by means of a dual task paradigm. In the current study, performance on the mental arithmetic task was influenced by both physical demand and exertion type. At a low force level, although participants made more errors, the performance was similar during both static and dynamic exertions. However, as the force levels increased, participants performed the arithmetic task less accurately in the static conditions compared to the dynamic conditions (Figure **10**). These trends were comparable with EMG activity, indicating a greater interference of mental demand with static exertions than dynamic exertions at higher force levels. Greater attentional costs or delay in information processing in the static exertions may be attributable, at least in part, to increased muscular load compared to dynamic exertions, evident by higher EMG activity, increased metabolic consumption, and increased perception of exertion, effort, and overall workload.

Subjective assessment of perceived effort and workload, measured by Borg CR10 ratings and NASA-TLX scores respectively, were both found to be sensitive to physical task parameters, such as force levels and type of exertion. Except for the Physical Demand subscale, all other components and overall workload score were also influenced by additional mental demands. In particular, participants perceived concurrent demand conditions at the low force level to be more demanding (with respect to Temporal Demand, Effort, Frustration, and overall workload) than the control, resulting in greater perception of failure than at higher force levels (Figure **11**). Recent work (Mehta & Agnew, in press, Chapter 2) evaluating subjective assessment of the interaction of physical and mental demands has demonstrated similar trends, highlighting sensitivity of NASA-TLX measures to specific force levels when studying concurrent task demands.

Gender was not found to influence physiological, performance, or subjective measures. As the physical workload levels were normalized to each participant's maximum static or dynamic shoulder strength, no physiological differences were expected. Although recent findings (Chapter 2) indicated gender bias in some NASA-TLX scores during static shoulder abduction, no such differences were found in the current study. Future research should thus focus on identifying gender differences in the perception of workload and validating psychometric tools that are sensitive to gender-based perceptions of demands. Personality type has been shown to influence perceived demand and muscle activity (Glasscock et al., 1999; Marras et al., 2000), however, due to lack of reliability on Type A scores obtained from the Jenkins Activity Survey, the effect of Type A tendencies on study outcomes were not analyzed.

Limitations and future directions

There are potential methodological issues and limitations that should be addressed. The effect of exertion type on physiological responses have been widely studied (Masuda et al., 1999; SoGaard, 1995; Vedsted et al., 2006), but only few studies provided comparable assessment of workload based on exertion type by employing identical time-tension products derived from static MVC (Stebbins et al., 2002; Vedsted et al., 2006). Physical workload conditions in the current study were derived from separate static and dynamic exertions (explained in the Methods section), to incorporate true muscle maximum for a given type of exertion. Static MVCs were performed at 45° arm abduction, whereas dynamic MVCs were collected when participants were instructed to maximally abduct their arm from their side to arm horizontal (range of motion = 90°). Although the work periods during both intermittent static and dynamic exertions were 5 seconds, the study did not employ identical time-tension product due to difference in the determination of physical workload levels. Despite this methodological issue, EMG measures during 15% and 30% MVC were comparable between the two types of exertions. At 50% MVC, EMG activity during static exertions were higher than dynamic exertions. It is possible that that the difference in static and dynamic MVCs may have potentially confounded the results. Future work should thus build on the results from the current study, by employing equivalent workload conditions to evaluate the effects of exertion type and concurrent demands on physiological and performance measures. The dynamic task employed in this study included an active phase of concentric contraction (i.e., shoulder abduction from arm at side to arm horizontal) and a passive return of the arm to original posture. As concentric and eccentric contractions have been shown to have differences in motor units activation patterns (Linnamo et al., 2003; Vedsted et al., 2006), it is unclear if these variations in neural activity would interact differently with concurrent physical and mental demands. Thus, in order to better understand the differential effects of exertion type on concurrent demands, further investigations that compare concentric and eccentric contractions with static exertions are warranted.

Mental arithmetic has been widely used as a laboratory stressor (Carter et al., 2005; DiDomenico & Nussbaum, 2008) and has been associated with increased mental stress (Allen & Crowell, 1989; Schleifer et al., 2008). Mental demands, induced using an arithmetic task in the current study, were representative of cognitive processing that workers experience with their tasks. However, these demands only constitute a portion of the psychological strain placed on workers (Bernard, 1997). Other psychosocial factors, such as time pressure, have been associated with increased upper extremity musculoskeletal disorders (Bongers et al., 1993; NRC, 2001). As such, future work should build on the findings from the current study, by considering the relative contributions of prevalent psychosocial risk factors and physical task parameters on the development of musculoskeletal disorders.

Conclusions

As static work is associated with increased risk of work-related musculoskeletal disorders, dynamic exertions are being employed to lower the risk of workplace injuries. Additionally, workers experience multiple demands in their daily jobs, such as concurrent physical and mental demands. However, it is unclear whether physiological responses are affected by exertion type; namely static and dynamic exertions, under combined demands. Results from this study highlight adverse effects of concurrent physical and mental demands during intermittent static work on shoulder muscle activity and coactivity, when compared to dynamic work. Further, static exertions were more susceptible to decrements in mental task performance than dynamic exertions, specifically at higher force levels. As such, it is important to consider the interaction of work parameters, specifically force levels and exertion type, when assessing overall task demands and worker performance during concurrent physical and mental work. The findings from this study have several practical implications. Tasks requiring concurrent physical and mental processing can be redesigned to reduce static loading of the muscles as well as improving task performance. Additionally, with tasks requiring static exertions, other physical parameters (such as force levels) can be manipulated/revised to minimize the interference due to additional cognitive processing. Thus, based on task specifications various redesign strategies can be adopted to reduce overall demands placed on workers that contribute towards the development of musculoskeletal disorders.

Chapter 4: Influence of mental workload on muscle capacity during intermittent static work

Abstract

Most occupational tasks involve some level of mental or cognitive processing in addition to physical work, yet existing ergonomic guidelines or tools do not consider these demands concurrently. The aim of this study was to quantify the interactive effects of physical and mental workload on muscle endurance, fatigue, and recovery during intermittent static shoulder work. Twelve participants, balanced by gender, performed intermittent static shoulder abductions to exhaustion at 15%, 35% and 55% of individual maximal voluntary contraction (MVC), in the absence (control) and presence (concurrent) of a mental arithmetic task. Changes in muscular capacity were determined using endurance time, strength decline, electromyographic (EMG) fatigue indicators, muscle oxygenation, and heart rate measures. Muscular recovery was quantified through changes in strength and physiological responses. Additional mental processing was associated with shorter endurance times, specifically at 35% MVC, and greater strength decline. Despite differences in endurance time, EMG and oxygenation measures showed similar changes during fatigue manifestation between the control and concurrent conditions. Moreover, decreased heart rate variability during concurrent demand conditions indicated increased mental stress. Although strength recovery was not influenced by concurrent demands, a slower cardiovascular recovery (elevated heart rate and lower heart rate variability) was observed after conditions requiring concurrent physical and mental processing. Findings from this study provide preliminary evidence that physical capacity (fatigability and recovery) is adversely affected by mental demands. These findings can aid in the assessment of capacity based on overall demands placed on workers and can contribute towards the revision of current ergonomic guidelines to incorporate concurrent evaluation of physical and mental demands.

Keywords: physical workload, mental workload, endurance, strength, fatigue, recovery

Introduction

Physical risk factors, such as high forces, static loading, and prolonged duration, play a predominant role in the development of work-related musculoskeletal disorders (WMSDs) (Bernard, 1997; Sommerich et al., 1993). Although psychosocial factors (such as intensified workload and time pressure) have also been associated with WMSDs (Bongers et al., 1993; Karasek et al., 1987), their relative contributions in the development of injuries are much less clear. Exposure to psychosocial stressors have shown adverse physiological manifestations, such as increased arterial blood pressure and heart rate (Hjortskov et al., 2004; Wahlström et al., 2002), elevated cortisol and norepinephrine levels (Gerra et al., 2001; Lundberg, 2002), and increased muscle sympathetic nerve activity (Callister et al., 1992).

During low-level static work, additional mental demand and/or mental stress have been shown to adversely influence shoulder muscle activity (Lundberg et al., 2002; Waersted et al., 1991). Lundberg et al. (2002) demonstrated that during separate processing of a motor and mental task, similar motor units from the trapezius muscle were recruited. Furthermore, during low-level exertions, additional mental stress has been shown to perturb joint stability; requiring compensatory muscle co-contraction and an increase in muscle tension (van Loon et al., 2001). It has been suggested that over a prolonged period of time, sustained muscle activity can lead to the development of WMSDs (Lundberg, 2002; Westgaard, 1999).

While most studies have reported increases in muscle tension during low-level static work with additional cognitive processing, findings from our recent work (Mehta & Agnew, in press, Chapter 1 & 2) indicate similar muscle activity at low force levels in the absence and presence of a mental arithmetic task. It could be argued that at low-level exertions, since force output was controlled, participants were able to maintain their exertion (and not overshoot their target) while mentally processing the arithmetic questions. However, muscular effort decreased during concurrent work at high force levels. Similar findings have also been reported for maximal voluntary contractions (MVC) (Macdonell & Keir, 2005) and submaximally at 40% MVC (Au & Keir, 2007). This interference may be attributed to the simultaneous activation of dorsolateral prefrontal cortex, which has shown increased activity during motor contractions (Dettmers et al., 1996) and during cognitive processing (Rowe et al., 2000). Under conditions of high physical effort, additional mental demand may reduce available attentional resources needed to increase the drive to motor neurons to maintain the required force levels (Welford, 1973), resulting in reduced muscular output. This decrease in muscular effort may result in increased motor impairment, indicated by higher force fluctuations.

Macdonell & Keir (2005) demonstrated a decline in peak shoulder strength with simultaneous cognitive processing. As a decrease in force generating capacity is an indicator of peripheral fatigue (Guillot et al., 2005; Holding, 1983), additional mental processing, over time, may potentially influence motor recruitment efficiency and fatigue development. In support of this hypothesis, Yoon et al. (2009) demonstrated that time to task failure during a sub-maximal contraction (at 20% MVC) is influenced by additional cognitive stressors. To determine work-rest allowances, ergonomists still rely on muscle endurance data developed by Rohmert (1962; 1973) and/or Garg et al. (2002), or alternate endurance prediction models that exist within the literature (reviewed in El ahrache et al., 2006). There is limited information on muscle endurance for tasks consisting of concurrent physical and mental demands. As such, there is a need to provide further empirical evidence on the influence on mental demand on muscle endurance.

It should be noted that the increase in muscle tension due to mental demands during low-level exertions may be modest when compared to that induced by physical demands. However, the increased muscle tension may result in prolonged activation of low threshold motor units during work, or during rest, and may negatively affect muscle recovery (Lundberg, 2002). Under combined demands, muscular rest is affected, with studies reporting fewer EMG gaps (Laursen et al., 2002; McLean & Quhart, 2002). Furthermore, recovery (after work) may also be hindered due to the continued secretion of catecholamines and cortisol due to non-work related stress (Melin & Lundberg, 1997; Sluiter et al., 2000). While slower recovery to baseline measures for interstitial norepinephrine was found during tasks requiring concurrent physical and cognitive processing (Flodgren et al., 2009), strength recovery was not influenced by cognitive stressors after a low-level fatiguing contraction (Yoon et al., 2009). In order to understand the effects of mental demand on recovery, further assessment of physiological and strength recovery patterns at varying force levels is necessary.

The purpose of the present study was to quantify changes in muscular endurance, fatigue, and recovery during intermittent static work at varying physical workload levels in the absence and presence of additional mental workload. Given the increasing shoulder injury rates (BLS, 2008) and sensitivity of shoulder muscles to increased mental demands (Waersted et al., 1991; Westgaard & Bjorklund, 1987), intermittent static shoulder abduction was employed as the physical task. Additional mental workload was presented as a serial-three multiplication arithmetic task. Similar arithmetic tasks (such as serial- seven or eleven subtraction) have been previously employed as laboratory cognitive stressors that have shown to successfully induce psychological stress (Allen & Crowell, 1989; Schleifer et al., 2008). Changes in muscular capacity were determined using endurance time, strength decline, electromyographic fatigue indicators, muscle oxygenation, and heart rate measures. Muscular recovery was quantified through changes in strength and physiological responses. Performance on the physical and mental task was also measured. Finally, subjective assessment of fatigue and workload was also conducted. It was hypothesized that tasks requiring concurrent physical and mental processing will adversely affect muscular capacity (i.e., endurance, fatigability, and recovery). Moreover, these changes will be dependent on physical workload levels.

Methods

Experimental Design

A 3 (physical workload) x 2 (mental workload) full factorial repeated measures design was employed to quantify changes in muscular endurance and recovery during, and following a bout of intermittent shoulder abductions. The independent variables in this study were:

1. Physical workload (PWL): Physical loads were induced as percent MVC of each subject at three levels: 15% MVC, 35% MVC, and 55% MVC.
2. Mental workload (MWL): Mental workload was manipulated at two levels: absence (control) and presence of a mental arithmetic task (concurrent condition).

Participants performed the six treatment conditions on separate days with a minimum of two days of rest in between. A Balanced Latin Square design was employed to determine the order of the treatment conditions to avoid order or learning effects.

Participants

Twelve participants (6 males and 6 females) were recruited from the local community, whose mean (SD) age, stature, and body mass were 21.21 (1.75) years, 1.51 (0.49) m, and 67.89 (11.08) kg, respectively. Participants were limited to right-handed individuals with no self-reported injuries, illnesses, or musculoskeletal disorders within the past year. Informed consent, using procedures approved by the Virginia Tech Institutional Review Board (**Appendix C**), was obtained prior to the experiment.

Procedures

Participants attended one preliminary session and six experimental sessions, with at least two days in between to avoid any fatigue or carryover effects. At the preliminary session, participants completed the informed consent procedure approved by the Virginia Tech Institutional Review Board and a student version of the Jenkins Activity Survey to determine Type A tendencies

(Jenkins et al., 1979; Yarnold & Bryant, 1994). They were familiarized with the experimental task, i.e. both physical task (intermittent static shoulder abduction) and mental arithmetic task. After the familiarization procedure, participants performed a series of MVCs (Nm) of the shoulder to determine the levels of physical workload. They were seated in a dynamometer (Biodex™ System 3 Pro Medical System, Shirley, New York, USA), comfortably secured at the shoulder and waist, with their right shoulder abducted at 90° (Figure **12).** Once settled, participants were instructed to maximally abduct their arm against the dynamometer padding, keeping the other arm resting at the side. A minimum of three MVCs was performed, with two minutes rest given between each MVC, and the maximum torque value from the three MVCs was used to determine physical workload levels. The MVCs were corrected for gravitational effects acting on the limb.

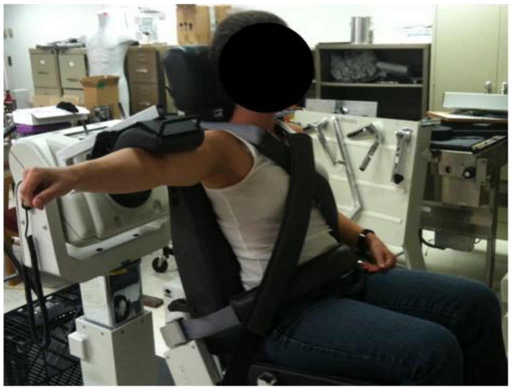


Figure 12. Participant posture for the endurance test.

Each experimental session comprised of familiarization, pre-MVC measurements, an endurance test, and post-MVC measurements during the recovery period. Participants performed sufficient warm-up exercises at the beginning of each experimental session before being instrumented with electromyography (EMG) electrodes (Measurement Systems Inc., Ann Arbor, MI, USA), near-infrared spectroscopy (NIRS) probe (OxiplexTS, ISS, Champaign, IL), and a heart rate monitor (RS800 Polar Heart Rate Monitor, Lake Success, NY). EMG signals from the three deltoid muscles (anterior, middle, and posterior deltoid) and upper trapezius were collected using 10 mm, rectangular Ag/AgCl pre-gelled bipolar electrodes. The middle deltoid has been shown to play a dominant role during shoulder abduction at 90º (Perotto, 1994; Yassierli et al., 2007), and was thus considered as the primary muscle from which EMG signals were obtained. To reduce skin resistance, the muscle sites were shaved and cleansed with alcohol, and electrodes were placed according to clinical procedures (Perotto, 1994). Raw EMG signals were pre-amplified near the collection site and hardware bandpass filtered (20-450 Hz). The NIRS probe was placed on the belly of the middle deltoid, aligned in the direction of the muscle fibers, and a heart rate strap was affixed to the skin near the midpoint of the participant's sternum. After a 20-minute stabilization period, a quiet trial and muscle-specific MVCs were obtained. Participants performed MVCs across several standardized postures that were assumed to elicit maximal strength output of each muscle under study.

After adequate rest, participants were secured in the Biodex™, with the experimental setup and posture similar to that employed in the preliminary session (Figure **12**). The experimental protocol is illustrated in Figure **13.** Baseline physiological measurements were collected for 2 minutes, following which participants performed three sets of isometric MVCs, and the maximum value of the three trials was used as the pre MVC. Given adequate rest, participants underwent the endurance test at one of the three PWL conditions. The endurance test required participants to perform intermittent static exertions, with 15 s of work and 15 s of rest, until exhaustion. Visual feedback was presented as a series of square waves displaying work and rest periods, thereby visually controlling the duration of the work-rest cycle. For the concurrent condition, participants performed the exertions while continuously performing a serial-three mental arithmetic task during the work periods. Specifically, a one- or two-digit number was randomly presented at the start of each work period and participants were instructed to multiply the number by 3, the answer by 3, and so on. They were instructed to perform as many multiplications as possible within the work period of 15 seconds as accurately as they could, while maintaining their force levels. They were instructed to start over again if they provided a wrong answer. After the intermittent static exertions were performed till exhaustion, participants performed a series of post MVCs at 0, 1, 2, 5, 10, and 15 minutes during the recovery period. Physiological measurements, i.e. EMG, muscle oxygenation, and heart rate measures, were continuously recorded for the entire trial. Performances on the physical and mental tasks were also collected. Ratings of perceived exertion (Borg CR10 scale) and workload scores (using the Subjective Workload Assessment Technique) were obtained intermittently during the endurance phase. The Swedish Occupational Fatigue Inventory (SOFI) was administered before and after the endurance phase to subjectively assess fatigue levels.

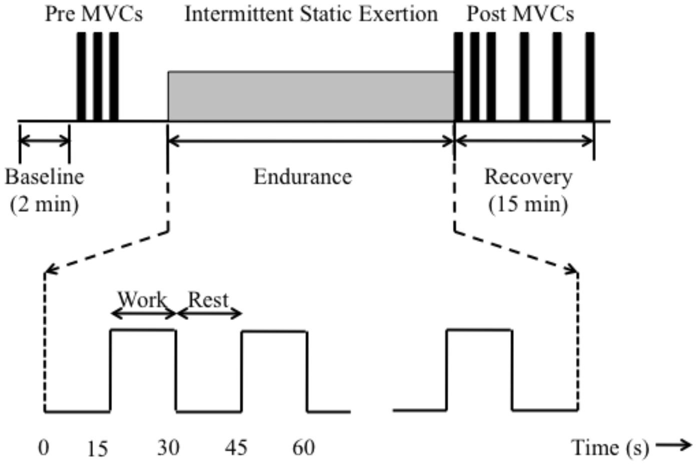


Figure 13. Experimental protocol. MVCs (black bars) were performed before the endurance phase (grey bar) and intermittently during recovery (at 0, 1, 2, 5, 10, and 15 minutes of recovery). Endurance phase comprised of intermittent static exertions at 15%, 30%, or 55% MVC (PWL levels) in the absence or presence of mental arithmetic task (MWL levels).

Outcome measures

The dependent measures included endurance time, physiological, motor performance, rate of MVC decline, and strength recovery measures. Change scores were utilized to quantify changes in the physiological and motor performance measures from the initial cycle to the last cycle.

Additionally, change scores on SOFI dimensions and rates of change on RPEs and SWAT scores were also determined. Endurance time was defined as the time to exhaustion while performing intermittent static exertions at the required target force levels. Additionally, rates of MVC decline were determined as the percentage reduction in shoulder strength ((post – pre)/ pre) relative to individual endurance time. A change score for strength recovery was calculated as ((MVC at 15th min of recovery – MVC at 0th min of recovery)/MVC at 0th min of recovery), where post MVCs were normalized to pre MVCs.

Physiological measures

Electromyography: EMG signals obtained during the trial were corrected for DC bias and band-pass filtered using a Butterworth filter at 20-450 Hz (dual pass, 4th order) using a custom program developed in LabVIEW (National Instruments, TX, USA). EMG amplitude and mean power frequency (MnPF) were obtained in 10-second windows in the middle of each 15-second work period. EMG amplitude was determined by full-wave rectifying and low-pass filtering raw EMG signals using a Butterworth filter (4th order, dual-pass, 3 Hz cut-off), and was corrected for resting amplitudes (obtained from the quiet trial). Processed EMG signals from each muscle were normalized with respect to its maximum value (processed similarly). A Hamming window and Fast-Fourier transform was applied on raw EMG data of the middle deltoid on 1-second windows to determine the power spectrum. MnPF was calculated for each window according to Merletti & Lo Conte (1995) and an average was determined for each window over the 10-second work period. Muscle coactivity was determined using a co-contraction index (CCI) for the shoulder that was calculated from EMG amplitude of the shoulder muscles, taken as the ratio of the antagonist muscle with respect to the agonist muscles, multiplied by the sum of the activity of all muscles (Rudolph et al., 2001). Increases in EMG amplitude and decreases in spectral parameters (mean or median power frequencies) have been associated with physical fatigue (De Luca, 1997). As such, change scores (calculated as (last work period – 1st work period)/1st work period) were utilized to assess fatigue development in the middle deltoid by quantifying increases in EMG amplitude and decreases in MnPF of the middle deltoid; increases in cocontraction (CCI) was similarly evaluated as well.

Muscle oxygenation: Muscle oxygenation measurements were collected non-invasively from the middle deltoid using a near-infrared spectrometer (NIRS). The system was calibrated according to the manufacturer's instructions, following which the probe was placed on the middle deltoid. The absolute value of percent saturation ($\%StO_2$) was recorded continuously for the whole trial (during endurance and recovery) and sampled at 2 Hz. The middle 10-seconds of data for each work period were utilized and averaged to obtain mean $\%StO_2$ per work period. A greater reduction in percent saturation has been associated with increased physical exertions and/or fatigue (Bhambhani et al., 1999; Praagman et al., 2003), and mentally demanding tasks (Heiden et al., 2005). Change scores were employed to determine reductions in $\%StO_2$ during the endurance phase and were calculated as (1st work period – last work period)/1st work period. Percent saturation in the recovery phase was averaged over 10 seconds before the post MVC at 15th minute of recovery, and $\%StO_{2Recovery}$ was calculated as ($\%StO_2$ before 15th min – $\%StO_2$ at baseline)/ $\%StO_2$ at baseline.

Heart rate measures: Heart rate (HR) data was recorded continuously as beat-to-beat (R-R) intervals, and average HR was calculated for the entire endurance phase, and intermittently during the recovery period. Heart rate variability (HRV) was calculated as the standard deviation in HR over the entire endurance phase (Malik et al., 1996). Average $HR_{Endurance}$ was used as a measure of physical workload and fatigue (Åstrand, 1967; Kilborn, 1971) and $HRV_{Endurance}$ was used to quantify changes in mental workload or stress (Kamath & Fallen, 1993; Meshkati, 1988). HR data in the recovery phase was averaged over 10 seconds before every post MVC, and

$HR_{Recovery}$ was calculated as (Baseline HR – HR before 15th min)/Baseline HR. Additionally, $HRV_{Recovery}$ was calculated as the standard deviation in HR over the entire recovery phase.

Performance measures

Force fluctuation was used as an indicator of motor performance, assessing steadiness in force generation (Christou & Carlton, 2002; Enoka et al., 2003). Force data were collected from the dynamometer for the endurance phase, sampled at 1024 Hz, and low pass filtered at 15 Hz. Force fluctuation was quantified though the coefficient of variation of the exerted force (calculated as standard deviation/mean force) for the middle 10-second window of each work (Enoka et al., 2003; Ranganathan et al., 2001). Change scores were employed to determine increases in force fluctuations and calculated as (last work period – 1st work period)/1st work period. Performance on the mental arithmetic task was recorded, as the average number of successful multiplications performed in each work period over the entire endurance phase.

Subjective measures

To determine levels of fatigue manifestation, the Swedish Occupational Fatigue Inventory (SOFI) was administered before (pre) and after (post) the endurance phase (**Appendix F**) (Ahsberg et al., 2000). Participants were asked to rate the extent to which they are feeling 20 distinct expressions (measuring five fatigue dimensions: Lack of Energy, Physical Exertion, Physical Discomfort, Lack of Motivation, and Sleepiness), using response scales ranging from 0 (not at all) to 6 (to a very high degree). Normalized change scores were calculated for all dimensions as (post – pre)/scale range. Additionally, participants rated their perceptions of workload using the Subjective Workload Assessment Technique (SWAT) questionnaire (**Appendix G**). SWAT measures overall mental workload using perceptions on three dimensions: Mental Effort Load, Time Load, and Stress (Reid & Nygren, 1988). A visual-analog scale (VAS) version of SWAT was employed in the current study, as it has been found to be sensitive in measuring different levels of mental workload (Luximon & Goonetilleke, 2001). Based on their perceptions on the three dimensions, participants were asked to place a mark on each VAS (length of VAS was 20 cm: low to high) that represents the magnitude of the task. Finally, participants provided ratings of perceived exertion (RPE) of the shoulder using the Borg CR10 scale (Borg, 1990) **(Appendix D)**. The scale ranges from "0, nothing at all" to "10, extremely strong", and has been shown to be strong indicators of physical fatigue (Ahsberg et al., 2000; Borg, 1982). SWAT and Borg CR10 ratings were collected intermittently throughout the endurance phase, and rates of change (slope) of these subjective measures, normalized to initial values, were used to indicate manifestation of physical fatigue, mental load, time pressure, and stress.

Analysis

Separate 3 (PWL) x 2 (MWL) repeated measures analyses of variance (ANOVAs) were conducted to determine changes in all dependent measures. A one-way ANOVA was conducted to assess the effect of PWL on performance on the mental arithmetic task. In all analyses, gender and order of exposure were included as blocking variables. Order had no effect on any dependent measure (all $p > 0.05$) and was thus removed from the final statistical model. Reliability analyses were performed on the SOFI fatigue dimensions, SWAT ratings, and on the items on the personality questionnaire (measuring Type A tendencies) using Cronbach's alpha. Acceptable to good reliability was found for the SOFI dimensions (Cronbach's alphas = 0.88 - 0.89) and SWAT ratings (Cronbach's alphas = 0.95 - 0.97) (Nunnally, 1978). As the Cronbach's alpha (standardized) values for all question items in the personality questionnaire were low (< 0.22), Type A scores were not included in the final statistical model. All dependent measures, except the subjective measures, demonstrated no substantial violations of parametric assumptions. Non-parametric Friedman test was employed to determine changes in subjective measures. Where required, post-hoc comparisons were conducted using Tukey's Honestly Significant Difference

(HSD) test. Statistical significance was determined when $p < 0.05$. All summary values are presented as means (SD).

Results

Significant main and interaction effects of PWL and MWL on objective measures of endurance, fatigue, and recovery are summarized in **Table 3**. Gender did not influence any dependent measures (all $p > .05$).

Table 3. Summary of ANOVA results (p-values) for the main and interactive effects of PWL and MWL on endurance, fatigue, and recovery measures. The symbol * indicates a significant effect ($p < .05$).

Measure	**PWL**	**MWL**	**PWL x MWL**
Endurance measures			
Endurance Time (min)	<0.0001*	0.032*	0.011*
Rate of MVC Decline (%/min)	<0.0001*	0.02*	0.132
Fatigue measures			
EMG-amplitude – middle deltoid (% Inc.)	0.100	0.633	0.797
EMG MnPF – middle deltoid (% Dec.)	<0.0001*	0.815	0.675
CCI (% Inc.)	<0.0001*	0.227	0.116
% Saturation (% Dec.)	0.001*	0.161	0.539
Avg. HR (bpm)	<0.0001*	0.864	0.135
HRV (msec)	<0.0001*	0.039*	0.406
Performance measures			
Force Fluctuation (% Inc.)	<0.0001*	0.873	0.733
Mental Task Performance	0.263	-	-
Recovery measures			
Strength (% Inc.)	<0.0001*	0.303	0.433
Avg. HR (% Dec.)	0.152	0.002*	0.684
HRV (msec)	0.208	0.004*	0.796

Endurance time

Shorter endurance times were associated with increased PWL levels ($p < 0.0001$) and additional mental workload ($p = 0.032$). More importantly, a significant interaction effect of PWL x MWL was found on endurance time ($p = 0.011$), with shorter endurance time observed only during moderate force levels (i.e. 35% MVC) in presence of mental arithmetic compared to the control condition (Figure 14).

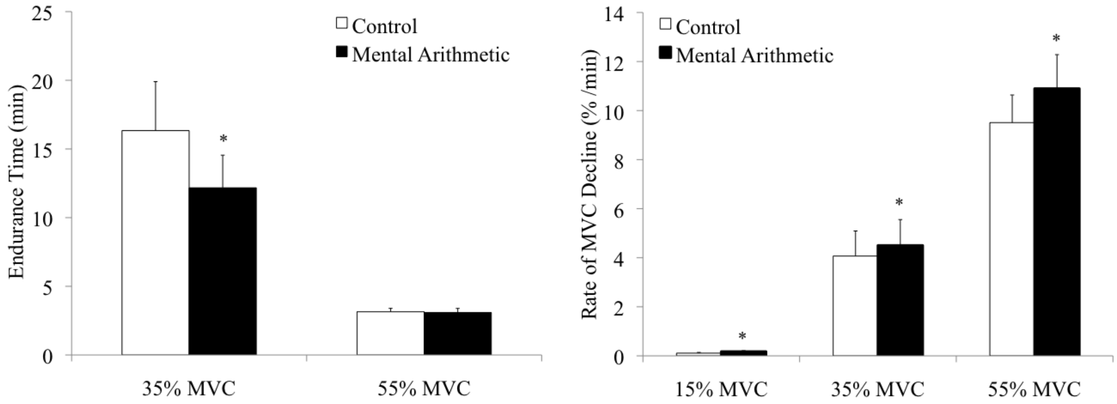


Figure 14. Influence of PWL and MWL on endurance time (left) and rate of MVC decline (right). Error bars represent standard error. The symbol * indicates a significant difference between the Control and Mental Arithmetic conditions.

Rate of MVC decline

Main effects of PWL ($p < 0.0001$) and MWL ($p = 0.02$) were found on rates of MVC decline (Figure 14), with greater strength decline observed at higher physical workload levels and in conditions requiring concurrent physical and mental processing. A marginal PWL x MWL interaction effect was also observed ($p = 0.132$), showing greater strength decline at higher physical levels in the presence of additional mental workload.

Fatigue measures

Physiological measures

Percent changes in EMG MnPF of the middle deltoid was significantly affected by PWL ($p < 0.0001$), with a decrease of 20.5 – 25.1% from initial values found at moderate and high PWL levels compared to 7.4% decrease at low PWL levels. There was no difference in the MnPF values with respect to MWL ($p = 0.815$), and no interaction of PWL x MWL was found ($p = 0.675$). EMG amplitude of the middle deltoid was not affected by either PWL ($p = 0.100$) or

MWL (*p* = 0.633), or their interaction (*p* = 0.797). However, changes in CCI were significantly affected by PWL level (p < 0.0001), with an increase of 81% from initial values found at moderate PWL level compared to 11.8 - 37% increase at low and high PWL levels.

Physical demand significantly decreased percent oxygen saturation (*p* = 0.001), with greater decreases observed at higher PWL levels (a decrease of 2 - 3% from initial value at moderate and high PWL) than at low PWL (an increase of 6% from initial value). Increasing PWL levels were associated with higher average heart rate (*p* < 0.0001), with an increase of 27 - 36% observed at moderate and high PWL with respect to low PWL. The effect of MWL was not significant; however a marginal significant interaction of PWL x MWL was found on average heart rate, with higher heart rate observed at low PWL during concurrent demand condition compared to the control (**Figure 15**). Heart rate variability was significantly affected by both PWL (*p* < 0.0001) and MWL (*p* = 0.039). Lower HRV was found at 15% MVC compared to 35% and 55% MVC, and in conditions requiring concurrent physical and mental processing compared to the control (Figure **15**).

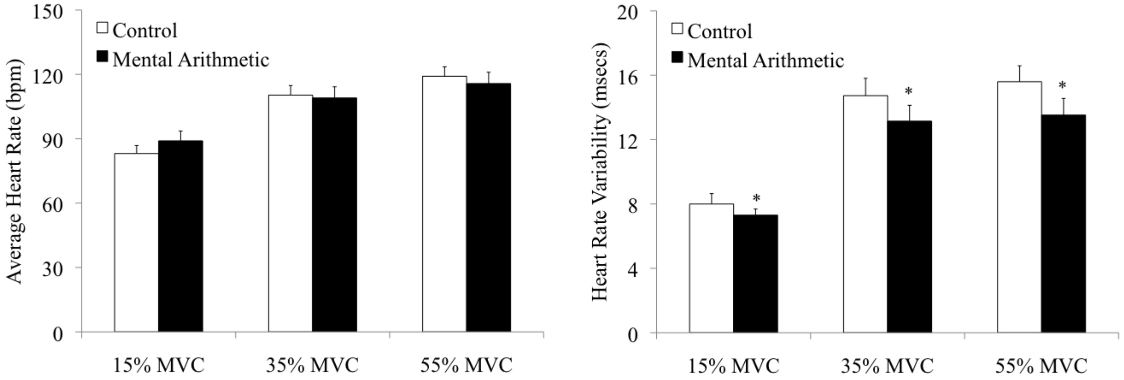


Figure 15. Influence of PWL and MWL on average heart rate (left) and heart rate variability (right). Error bars represent standard error. The symbol * indicates a significant difference between the Control and Mental Arithmetic conditions.

Performance measures

Greater increases in force fluctuations were found at moderate and high PWL (an increase of 117 - 137% from initial values), compared to low PWL (a decrease of ~8% from initial value). The effect of mental demand was not significant (*p* = 0.873), and no PWL x MWL interactions were found (*p* = 0.733). Participants performed an average of 1.57 - 1.81 successful multiplications per work period and the mental task performance was not affected by PWL (*p* = 0.263).

Subjective measures

In general, three of the five SOFI fatigue scores (i.e., Lack of Energy, Physical Exertion, and Physical Discomfort) increased significantly during all experimental conditions. In contrast, Lack of Motivation and Sleepiness scores decreased by 4 – 10% during moderate and high PWL. PWL significantly affected all SOFI scores (Table **4**). In particular, participants perceived greater fatigue at moderate PWL levels, compared to low or high PWL levels. Additional mental workload significantly decreased Lack of Motivation score (-7.5% vs. -3.3% in the control condition). Although not significant (*p* = 0.172), the interaction of PWL x MWL suggested that the decrease in Lack of Motivation score was more pronounced at moderate PWL levels. MWL had a borderline main effect (*p* = 0.059) and a significant interaction effect of PWL x MWL (*p* = 0.009) on Sleepiness; with participants reporting higher scores in the control (2.7%) compared to concurrent demand conditions (-5.3%), more so at moderate PWL levels (Table **4**).

Table 4. Summary of ANOVA results (p-values) regarding the effects of PWL (at Low, Moderate, and High levels) and MWL (Control and MA: Mental Arithmetic) on perceived fatigue measures. The symbol * indicates a significant effect ($p < 0.05$). SOFI measures are normalized change scores, and are presented as means (SD).

	PWL	**MWL**	**PWL x MWL**	**Low**		**Moderate**		**High**	
Measure	***p***	***p***	***p***	**Control**	**MA**	**Control**	**MA**	**Control**	**MA**
Lack of Energy	<0.0001*	0.862	0.449	8.93 (18.05)	9.82 (16.34)	43.75 (20.72)	43.45 (21.42)	33.93 (24.63)	29.76 (18.48)
Physical Exertion	<0.0001*	0.705	0.290	3.57 (4.03)	5.36 (5.80)	31.25 (16.69)	30.95 (15.10)	22.62 (18.42)	17.26 (18.95)
Physical Discomfort	<0.0001*	0.862	0.503	6.55 (12.17)	7.74 (7.59)	25 (18.65)	23.21 (15.27)	17.56 (21.02)	17.56 (17.19)
Lack of Motivation	0.026*	0.016*	0.172	1.49 (8.12)	-3.57 (7.46)	-5.06 (13.49)	-10.42 (14.48)	-6.25 (12.19)	-8.63 (11.13)
Sleepiness	0.011*	0.059	0.009*	18.45 (20.7)	1.79 (14.8)	-3.87 (16.22)	-8.33 (15.48)	-6.55 (9.24)	-9.52 (20.95)

Rates of RPE and the three SWAT dimensions (i.e. Time Load, Mental Effort Load, and Stress) were all significantly affected by PWL (all $p < 0.0001$), with participants reporting greater increases in these ratings at higher PWL levels. No significant effects of MWL or its interaction with PWL were found on rates of RPE increase (both $p > 0.347$). In contrast, additional MWL was found to increase rates of all SWAT dimensions ranging from 2.29 – 2.4/min in concurrent demand conditions compared to 0.59 – 1.02/min in the control conditions (all $p < 0.0001$). Furthermore, a significant interaction effect of PWL x MWL was found on all SWAT dimensions (all $p < 0.0001$); additional mental workload was associated with rapid increases in the three SWAT dimensions at higher physical workload levels (Figure **16**).

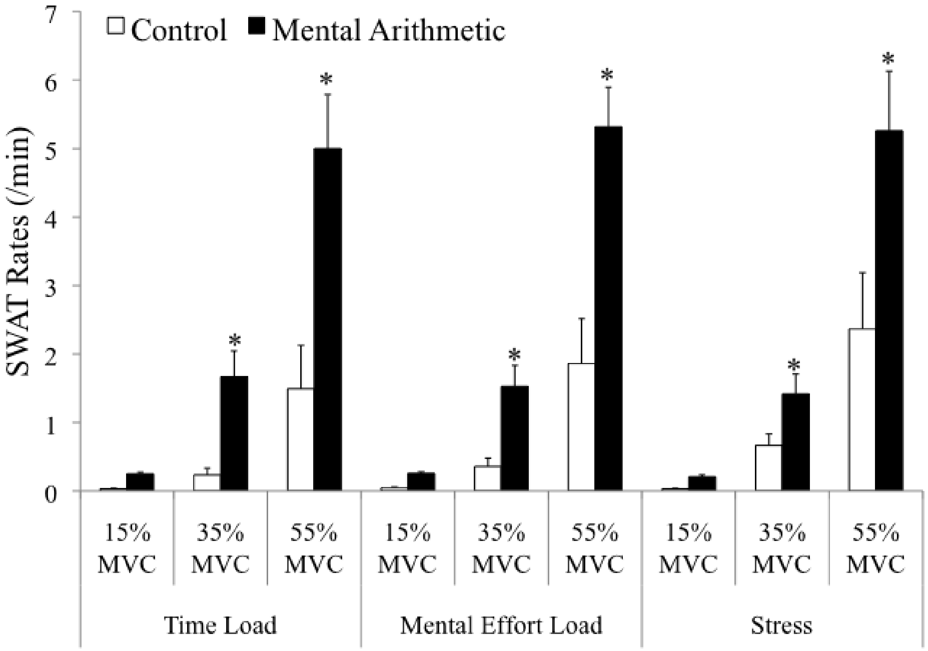


Figure 16. Influence of PWL and MWL on rates of SWAT dimensions (Time Load, Mental Effort Load, and Stress). Error bars represent standard error. The symbol * indicates a significant difference between the Control and Mental Arithmetic conditions.

Recovery measures

Strength recovery

A greater increase in strength recovery was found at higher PWL levels ($p < 0.0001$). Specifically, strength recovery was higher at moderate PWL compared to high and low PWL levels (Figure **17**). Additional mental workload did not influence strength recovery ($p = 0.303$), and no interactive effects were found ($p = 0.433$).

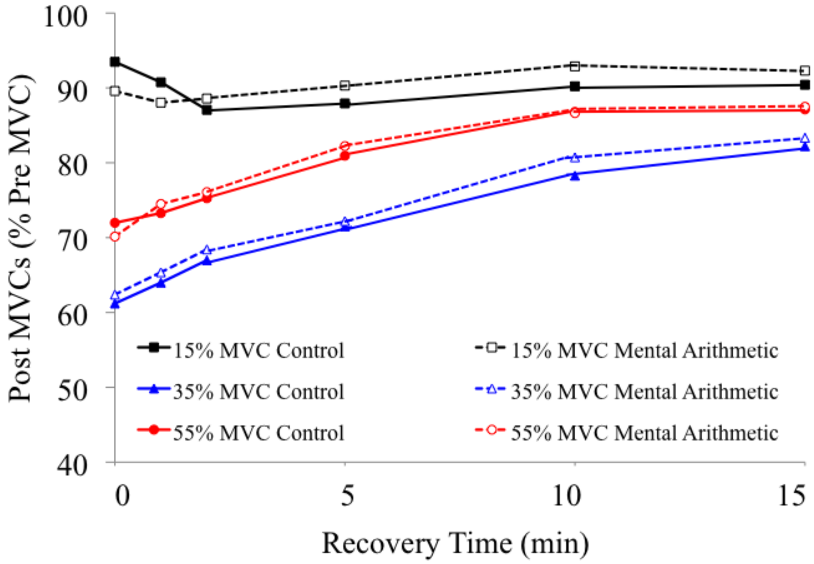


Figure 17. Post MVC trends during recovery. Post MVCs are normalized with respect to pre MVC.

Physiological recovery

There were no main or interactive effects of PWL and MWL on the recovery of percent oxygen saturation ($p > 0.645$), indicating similar recovery states across all treatment conditions. Furthermore, PWL did not influence average $HR_{Recovery}$ ($p = 0.152$) or $HRV_{Recovery}$ ($p = 0.208$). However, smaller decreases in average HR were found in conditions requiring additional mental workload ($p = 0.002$) compared to the control conditions, indicating slower cardiovascular recovery (Figure **18**). Furthermore, $HRV_{Recovery}$ decreased by 10.3% in conditions requiring concurrent physical and mental processing compared to the control. No interactive effects of PWL x MWL were found on average $HR_{Recovery}$ or $HRV_{Recovery}$.

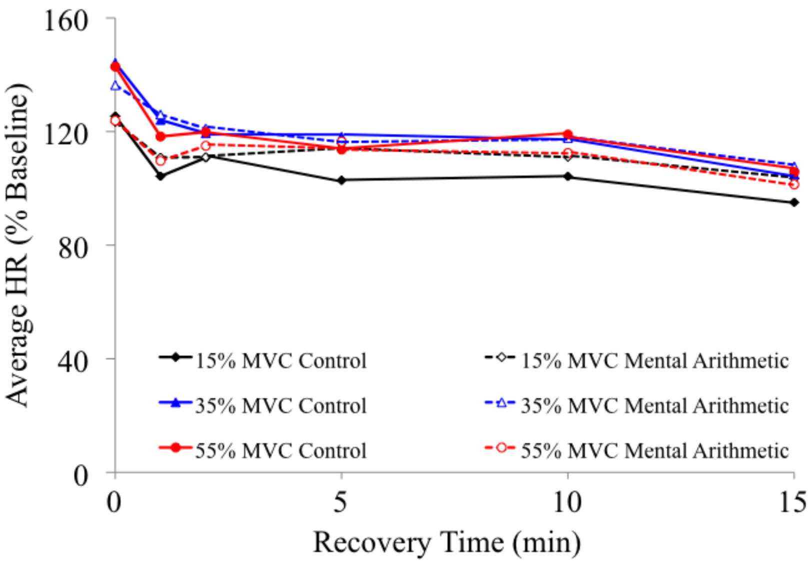


Figure 18. Average heart rate (HR) during recovery. HR data is normalized with respect to baseline HR.

Discussion

The current study aimed to quantify the interactive effects of physical and mental workload on muscle endurance, fatigue, and recovery during intermittent static shoulder work. Key findings include: (1) substantial decrease in muscular capacity (i.e. endurance and strength decline) during concurrent physical and mental processing, (2) similar physiological changes during fatigue manifestation, and (3) slower cardiovascular recovery with concurrent demands.

Muscle endurance and fatigue

Findings from this study confirmed the adverse effects of increasing physical workload on endurance time and strength decline (Garg et al., 2002; Milner-Brown et al., 1986). Additional mental workload also adversely influenced endurance time, and this effect was more prominent at 35% MVC. These results align with the findings obtained by Yoon et al. (2009) who reported a decrease in time to task failure due to cognitive stressors during low-level (20% MVC) sustained contractions. It has been shown that fatiguing contractions require high attentional demands due to changes in the excitability of motor cortex (Gandevia, 2001). As such, it could be argued that additional mental demand in the current study may have reduced available attentional resources needed to increase the drive to motor neurons to maintain the required force levels (Lorist et al., 2002; Welford, 1973), resulting in early task failure (i.e. shorter endurance times). Along with a decrease in muscle endurance, concurrent demand conditions also caused faster rates of strength decline, indicating an earlier onset of peripheral fatigue under these conditions.

Changes in EMG amplitude and power frequencies have been widely used to determine muscle fatigability (De Luca, 1997; Petrofsky et al., 1982). More recently, decreases in muscle oxygenation, measured using NIRS, have also been associated with fatigue (Yoshitake et al., 2001) and endurance (Tachi et al., 2004). In the present study, fatigue-induced changes in temporal and spectral EMG measures were similar between the concurrent and control conditions within each physical workload level, despite shorter endurance times observed during concurrent demand conditions. Concurrent demands were also suggested to result in greater reduction in oxygen saturation at higher physical workload (3.2 – 4.2%) compared to control conditions (0.46 – 1.8%). These findings suggest that similar states of fatigue were reached at the end of each condition within each physical workload level, in the absence and presence of additional mental workload.

Lower heart rate variability in concurrent demand conditions indicated high mental workload levels due to the arithmetic task (Hjortskov et al., 2004; Meshkati, 1988). As participants performed the task for a longer duration at 15% and 35% MVC (12 – 60 minutes) than at 55% MVC (~4 minutes), it could be argued that greater mental stress was placed on them that may have attributed to the decreased heart rate variability at lower physical demand levels. This was followed by increases in heart rate due to mental arithmetic during low physical workload (Callister et al., 1992; Yoon et al., 2009). Results from our previous work (Chapter 2) suggested that there was no differential effect of mental workload on heart rate at varying physical levels.

Thus, the discrepancies in interactive effects of physical and mental demands on heart rate warrants further investigation.

Previous studies investigating the interactive nature of physical and mental demands have primarily focused on performance-based effects of these concurrent demands. While it is generally accepted that performance is associated with changes in arousal of the central nervous system (Welford, 1973; Yerkes & Dodson, 1908), no force-related changes in mental task performance were observed in the current study. Our recent work on quantifying performance-based effects of concurrent demands has consistently shown an inverted U-shape; with greater performance decrements observed at lower and higher force levels (Chapter 2 and Chapter 3). Although it was determined that the arithmetic task employed in the current study induced sufficient mental stress, evident by lower heart rate variability, the performance measure employed may not have been sensitive to capture force-related changes. Performance on the mental task was recorded as the average number of successful multiplications performed per cycle, and in general, most participants were able to complete 1 – 3 successful multiplications. Future work is thus needed, by employing more sensitive performance measures, to quantify fatigue-related changes in mental task performance.

Interestingly, the effect of mental workload on endurance time was more pronounced at 35% MVC (Figure 14). While much of the research on concurrent demands have focused on low-level static exertions, a few studies have highlighted stronger interference by cognitive demands during higher force production (Macdonell & Keir, 2005; Zijdewind et al., 2006). Although shorter endurance times were observed at 55% MVC during concurrent demand conditions compared to the control (3.09 (1.04) vs. 3.15 (.86)), these differences were not significant. Despite the discrepancy of force-related effects of mental demand on endurance times, similar rates of strength decline due to mental demand were evident across all physical workload levels.

While endurance time (i.e. time to task failure) indicates a specific point in time when the muscle is unable to maintain the required force level (Hagberg, 1981; Hainaut & Duchateau, 1989), strength decline relates to progressive fatigue manifestation (Fitts, 1996; Holding, 1983; Vøllestad, 1997) and is thus generally accepted as a “gold standard” indicator of fatigue (Vøllestad, 1997).

Although muscle fatigue has been associated with discrete (endurance time) or continuous (strength decline) changes in muscle capacity, it consists of two distinct components: peripheral and central fatigue. Peripheral fatigue is associated with accumulation of metabolites and changes in the contractile elements (Guillot et al., 2005; Lorist et al., 2002), whereas central fatigue relates to changes in the central nervous system that drives motor behavior (Holding, 1983). Intrinsic factors, such as motivation, and task-related factors, such as mental fatigue, have been argued to influence central fatigue (Boksem et al., 2006; Chaudhuri & Behan, 2000; Grandjean, 1968). With regards to findings from the current study, it is possible that participants reached a state of mental fatigue when performing mental arithmetic at 15% and 35% MVC, owing to the longer task durations (Chaudhuri & Behan, 2000). Coupled with higher force production (at 35% MVC), participants may have reached a state of central fatigue during concurrent demand conditions resulting in an earlier failure point (or shorter endurance times). Neither mental fatigue nor central fatigue was formally assessed in the current study, thus future work should build on the results obtained here and consider formal evaluation of different components of fatigue (physical versus mental; peripheral versus central) during concurrent physical and mental processing.

Perceived fatigue measures (SOFI scores) were sensitive to changes in physical workload. Interestingly, participants perceived greater physical fatigue (Physical Exertion and Physical Discomfort) and overall fatigue (Lack of Energy) at moderate workload level compared to low and high levels. Scores on Lack of Motivation and Sleepiness suggested an increased mental arousal state at higher physical workload levels and during concurrent demand conditions. RPEs and SWAT dimensions (Time Load Load, Mental Effort Load, and Stress) increased rapidly with increases in physical workload. SWAT dimensions were also sensitive to additional mental workload. In general, participants perceived concurrent demand conditions to be more mentally challenging, pressed for time, and stressful compared to control conditions. Moreover, these perceptions rapidly increased at higher workload conditions.

Recovery

In general, irrespective of the treatment conditions, participants were unable to completely regain their strength (82 – 90% of baseline values) at the end of the recovery phase. Strength recovery was not influenced by mental demands during the endurance phase. Yoon et al. (2009) demonstrated similar trends, indicating that cognitive stressors do not influence strength recovery. Muscle oxygenation recovery was similar across all treatment conditions, with percent oxygen saturation at the end of the recovery phase reaching baseline values. Similar findings have been reported by Flodgren et al. (2009) during low-level repetitive work and simultaneous mental processing. Compared to the control, concurrent demand conditions resulted in slower cardiovascular recovery. At the end of the recovery phase, average heart rate ranged from 103 – 107% (% baseline) after concurrent demand conditions compared to 95 – 105% after control conditions. Furthermore, lower heart rate variability during recovery was observed after concurrent demand conditions compared to the control. Of note, heart rate is considered as an index of sympathetic activation (Callister et al., 1992); the latter plays a role in releasing catecholamines (i.e. epinephrine and norepinephrine) (Roatta et al., 2003). As norepinephrine has been associated with delayed recovery after concurrent physical and cognitive processing (Flodgren et al., 2009), a slower heart rate recovery may be attributable, at least in part, to elevated norepinephrine levels during recovery.

Limitations and future directions

A few limitations in the present study warrant discussion. First, the study concentrated on the effects of concurrent demands on shoulder muscle capacity by employing a controlled posture. Findings from our previous work (Chapter 2) indicated a greater susceptibility of shoulder muscles to concurrent demands. Furthermore, to control inter-individual variability in muscle recruitment patterns, a specific shoulder posture was studied in isolation. As strength and endurance are influenced by changes in postures and muscle fiber composition, future work should consider investigating mental demand-related changes in muscle capacity with different postures and muscle groups. Second, physical workload was manipulated at three levels: low, moderate, and high. Existing endurance data extends over several levels of physical exertion (Garg et al., 2002; Rohmert, 1962), thus additional work is warranted to determine a dose-response relationship. Similarly, mental workload was presented at two levels: absence and presence of mental arithmetic. Mental arithmetic was employed, as it required cognitive processing that is representative of mental demands placed on workers at their daily jobs. However, workers experience different levels of mental workload, thus it is important to consider multiple levels of mental workload when determining its effect on muscle capacity. Future work should build on the findings of the current study, by investigating the fatigue-related effects of different cognitive stressors (laboratory-based or occupationally relevant) at multiple levels on varying levels of physical workload. Third, the study employed an intermittent static task of 50% duty cycle. Although intermittent work is more representative of occupational tasks, intermittent rest periods may have masked physiological effects of mental demands and potentially influenced fatigability and recovery. Future work is thus needed to assess changes in muscle capacity due to concurrent demands at different work-rest paradigms and during sustained exertions.

Conclusions

Designing tasks or determining task demands requires consideration of worker capacity. Even though most occupational tasks (physical activities) involve some level of mental or cognitive processing, existing ergonomic guidelines or tools do not consider these demands concurrently. Findings from this study provide preliminary evidence that physical capacity is adversely affected by mental demands. Additional mental processing was associated with shorter endurance times, greater strength decline, increased fatigability, and slower cardiovascular recovery. Muscle endurance data has been widely published (Garg et al., 2002; Rohmert, 1962); however it is focused solely on physical factors, such as force levels and postures. As per our knowledge, this study has been the first to examine the capacity-related adverse effects of mental demand over a range of submaximal force levels. These findings can aid in the assessment of capacity based on overall demands placed on workers and can contribute towards the revision of current ergonomic guidelines, specifically endurance curves, to incorporate concurrent evaluation of physical and mental demands.

Several practical implications arise from the results obtained in this study. While faster fatigue-induced strength decline was observed under conditions of physical and mental processing, this effect was consistent across a range of physical workload levels. Thus, duration of tasks, characterized by concurrent physical and mental demands, should generally be reduced to avoid undue fatigue. Further, tasks can be redesigned, by incorporating design principles or facilitating serial rather than parallel physical and mental processing to reduce cognitive loads placed on workers (Wickens & Hollands, 2000), or by incorporating engineering controls to lower physical demands placed on workers. With 8 – 10 hours shift-work, fatigue (physical or mental) is inevitable. Thus, administrative controls, such as rest breaks or job rotation, can be implemented that not only provides passive and active muscle recovery, but also offer variation in mental workload that may hinder mental fatigue.

Chapter 5: Conclusions

Work-related musculoskeletal disorders (WMSDs) have been a major cause of disability and decreased productivity in the workplace. The World Health Organization (1985) emphasizes a multifactorial etiology of WMSDs (WHO, 1985), with physical work demands, psychosocial factors, and individual differences contributing significantly to the cause of the disorder. Although the causal pathways of WMSDs due to physical risk factors have generally been established, the etiology of WMSDs due to psychosocial factors and individual differences is not clearly understood. Research is needed to help understand these multifactorial pathways of development of WMSDs and to facilitate development of ergonomic guidelines and interventions.

Occupational tasks place both physical and psychological strain on workers, which can ultimately result in the development of work-related musculoskeletal disorders (WMSDs). Yet, existing research focusing on WMSD development or ergonomic interventions do not address the interaction between mental and physical demands associated with occupational tasks. Although the intensity of mental demands alone may not be causal in the development of WMSDs, its interaction with physical demands have consistently been associated with increased muscle tension and cardiovascular responses (Hjortskov et al., 2004; Lundberg, 2002). However, whether muscle capacity is altered with these concurrent demands remains unclear. While the adverse effects of concurrent physical and mental demands have been well documented during low-level static exertions (Waersted, 2000), there is still a need to understand how concurrent demands interact with different work parameters, such as force levels, muscles employed, and types of exertion. The current research was conducted to address these needs through three experimental studies by evaluating changes in physiological, performance, and subjective measures during intermittent work.

Research summary and contributions

The results from the first study provided evidence on the interactive nature of physical and mental demands on physiological responses, performance, and subjective measures during intermittent static work. The differential effects of mental demands suggest that higher force levels are more susceptible to motor inefficiencies, increased cardiovascular loading, and impairment of motor and cognitive performance. Thus, work involving simultaneous physical and cognitive processing should either lower physical task demands or facilitate cognitive processing through engineering and administrative controls. Compared to the wrist, the shoulder and torso muscles showed greater performance impairment in conditions requiring concurrent physical and mental work. Thus when designing work tasks, tools, and/or workstations, it may be important to consider these muscle-specific interactions of concurrent demands.

The aim of the second study was to compare exertion-dependent physiological responses due to concurrent physical and mental workload during intermittent static and dynamic shoulder exertion. The results from this study demonstrated that static exertions were more susceptible to concurrent physical and mental demands than dynamic exertions. This finding further supports existing evidence that static work places greater muscular and metabolic load and that additional mental demand further exacerbate these outcomes. Further, mental task performance was adversely affected at high levels of static exertions. Results obtained in this study emphasize the importance of these interactions of common work parameters (force levels, mental demand, type of exertion) in job design. Primarily, static loading should be minimized in tasks associated with high physical and cognitive demands. With tasks that involve static exertions, other physical parameters (such as force levels) should be reduced to minimize the interference due to additional cognitive processing.

The final study provided fundamental evidence on the adverse effects of concurrent demands on muscle capacity during intermittent static work. While the adverse effects of additional mental demand on endurance time was more pronounced at moderate physical demand level, greater fatigue-induced strength decline was observed during concurrent physical and mental work across all levels of physical demand. Nonetheless, both measures (i.e. endurance time and strength decline) indicated that mental demand accelerated muscle fatigability and affected worker capacity. To alleviate these adverse effects of concurrent demands, several recommendations are provided. First, proactive workload determination of work tasks should be based on the "overall" demands of the task and "modified" capacity of the worker to minimize undue strain on the worker. Second, concurrent demands exacerbate muscle fatigability. Thus, additional rest breaks should be provided to hinder fatigue progression for occupational tasks that are characterized with high levels of physical and mental workload. Third, tasks should be redesigned such that the interference due to concurrent demands is minimized. This can be achieved by adopting different workload reduction strategies, such as serial versus parallel processing of physical and mental demand, employing design principles from human information processing domain (such as affordances and redundant coding) to reduce cognitive demands, and varying physical task parameters (by modifying force levels or employing different muscle groups). Finally, sufficient recovery should be provided post work.

The findings from these three studies as a whole provide a better understanding of the causal relationships between different work demands and WMSD development. The conceptual model that guided this research is presented again in Figure **19**. In summary, the mutual effects of physical and mental demands were found to influence physiological responses, such as muscle activity and heart rate measures. Furthermore, these interactions were influenced by work parameters, such as type of exertion and the muscle groups employed. Over prolonged duration, these overall demands adversely affected muscle endurance, fatigue, and recovery. Although the current research did not investigate the link between physiological/fatigue outcomes and development of WMSDs, the outcome measures employed in these studies have been linked with increased WMSD risk. Individual factors, such as gender and Type A tendencies, were included in the experimental design to investigate their influence on the interactive effects of concurrent demands. Although gender differences were found for some cognitive performance and subjective (i.e., NASA-TLX scores) measures, these were not consistent across the three studies. Moreover, no gender differences were observed for physiological and motor performance measures. Although personality scores (Type A tendencies) were obtained from the participant pool, due to the lack of reliability on these scores, they were consequently removed from the experimental design.

Issues concerning manipulation of mental workload in the current research warrant some discussion. The scope of this research was to investigate the effects of mental workload and its interaction with various physical task parameters on physiological, performance, and subjective measures. With the advancement of industrial automation, an increasing amount of mental workload is placed on workers along with the physical demands due to the tasks. As such, intensified workload has been strongly associated with pain symptoms and risk of WMSDs (Bernard, 1997). Numerous laboratory studies have employed cognitive stressors, such as the Stroop Color Word test (Macdonell & Keir, 2005; Mehta & Agnew, in press) and mental arithmetic tasks (Carter et al., 2005; Schleifer et al., 2008), to investigate the effects of mental workload and/or stress on physiological responses. In particular, mental arithmetic has been used widely to induce mental workload/stress as it has shown distinct changes in physiological responses (Schleifer et al., 2008) and requires cognitive processing that is representative of mental demands placed on workers at their daily jobs.

Research indicates a central role of working memory (i.e., limited-capacity central executive, phonological loop, and visual-spatial sketchpad) in the solution of mental arithmetic tasks (DeStefano & LeFevre, 2004; Zago et al., 2001). Specifically, mental arithmetic processing requires mental activities such as accessing memory representation, retention of intermediate solutions, and assembly of an answer, which requires actions from the visual-spatial sketchpad (that is responsible for holding and manipulating visual images) (Trbovich & Lefevre, 2003). In the current research, with the physical task requiring participants to maintain a target force/moment level through biofeedback, the interference (i.e., competing for attentional resources from a limited resource pool) may have been caused at the visual-spatial sketchpad due to additional mental arithmetic processing. It is suggested that the dorsolateral prefrontal cortex region of the brain may be responsible for this interference as it is involved in tasks related to working memory and response selection (Rowe et al., 2000) and has shown increased activity during isometric motor contractions (Dettmers et al., 1996).

Potential phases at the workplace and worker level) where the adverse effects of concurrent demands can be minimized are identified in Figure **19**. First, at the workplace level, engineering and administrative controls can be employed to redesign tasks to reduce “overall demands” placed on workers. These controls can include changes in tool/product design, workstation design, workload levels, and task parameters. Second, at the worker level, incorporating various work-rest paradigms or facilitating job rotation can reduce the effects of concurrent demands on physiological responses and fatigue development. Finally, sufficient recovery should be provided such that workers are able to “unwind” physiologically.

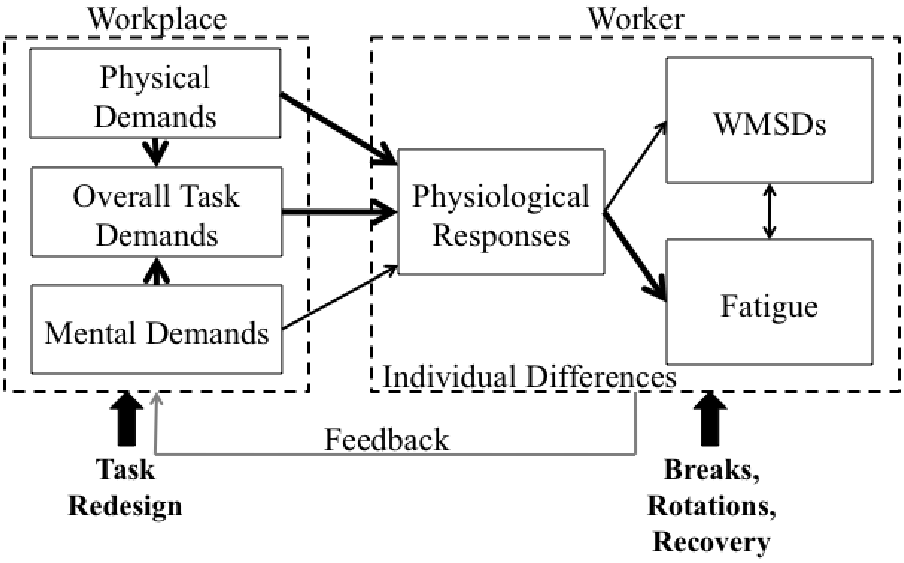


Figure 19. Conceptual model of WMSD development. Dark arrows indicate the causal pathways investigated in the current research. Block arrows highlight potential areas of ergonomic interventions.

Research limitations and future directions

The scope and limitations in the current research can be addressed in future research. First, while the current research expanded our knowledge on the influence of a mental arithmetic task at varying levels of physical demand, the nature and intensity of psychological and psychosocial demands vary in different occupations. Thus, future work will build on the results obtained here, by evaluating effects of other cognitive and psychosocial stressors, both laboratory-based and that representative of occupational tasks, at multiple levels. Second, one of the motivations of the current research was to investigate the effects of concurrent demands in controlled laboratory conditions that are occupationally relevant. Future work will expand on findings from the current research to field-based assessment of multiple risk factors in difference occupational settings that would provide additional information of the causal mechanisms of injury development. Third, the final objective of the research was to provide evidence on the adverse effects of concurrent demands on muscle capacity. The present work is an initial step toward developing a dose-response relationship between levels of concurrent demands and muscle endurance. Knowledge gained from the current research and future work can be utilized to determine rest allowances for tasks requiring concurrent physical and mental processing.

Individual differences (gender and Type A tendencies) were included in the current research, but not much information on their influence on concurrent demands could be obtained. Future research will include more systematic investigation of worker characteristics on outcome measures. For example, age-related changes in neuromuscular control and cognitive processes could influence dose-response relationship between concurrent demands and muscle capacity. Thus, future work should consider the effects of concurrent demand on worker health and performance for the aging workforce. Factors, such as I.Q. and education, can influence performance on specific cognitive stressors (e.g. mental arithmetic test). However, in the current research, the majority of the participants were recruited from a pool of graduate and undergraduate engineering student body. Thus, the participant pool may be assumed to have a relatively similar educational background, and intellectual ability.

Finally, the current research adopted an experimental research-based approach towards (1) understanding causal pathways of injuries due to concurrent demands and (2) identifying suitable ergonomic interventions to minimize the risk of WMSD development due to these demands. Future work should expand on the knowledge gained by this research, by facilitating revisions of existing ergonomic guidelines to incorporate mutual effects of concurrent demands (e.g., providing correction factors for cognitive processing) and by investigating the efficacy of ergonomic interventions to reduce detrimental effects of concurrent demands on worker capacity (such as task redesign, work-rest paradigms).

Final conclusions

Overall, the current research provided a comprehensive understanding of the interactive effects of physical and mental demands on short-term physiological responses and task performance and on gradual fatigue manifestation. Human factors practitioners currently evaluate effects of physical and mental demands in isolation; results from this research necessitate concurrent assessment of these demands. These findings may facilitate the development of task redesign strategies to help reduce risk of workplace injuries and improve worker performance. Finally, outcomes from this research can contribute towards the revision of current ergonomic guidelines (such as endurance data) to incorporate concurrent assessment of physical and mental demands.

References

Ahsberg, E., Gamberale, F., & Gustafsson, K. (2000). Perceived fatigue after mental work: An experimental evaluation of a fatigue inventory. *Ergonomics, 43*(2), 252-268.

Allen, M., & Crowell, M. (1989). Patterns of autonomic response during laboratory stressors. *Psychophysiology, 26*(5), 603-614.

Åstrand, I. (1967). Degree of Strain during Building Work as related to Individual Aerobic Work Capacity. *Ergonomics, 10*(3), 293-303.

Astrand, P., & Rodahl, K. (1986). *Textbook of work physiology* (3rd ed.). New York: McGraw-Hill.

Au, A. K., & Keir, P. J. (2007). Interfering effects of multitasking on muscle activity in the upper extremity. *Journal of Electromyography and Kinesiology, 17*, 578-586.

Bernard, B. P. (1997). Musculoskeletal disorders and workplace factors: a critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back. *U.S. Department of Health and Human Services CDC (NIOSH), Publication No. 97-141*.

Bhambhani, Y., Buckley, S., & Susaki, T. (1999). Muscle oxygenation trends during constant work rate cycle exercise in men and women. *Medicine & Science in Sports & Exercise, 31*(1), 90.

Bigos, S., Battie, M., Spengler, D., Fisher, L., Nachamsin, A., & Wang, M. (1986). Back injuries in industry: A retrospective study. II. Injury factors. *Spine, 11*, 1-6.

Bigos, S. J., Battie, M. C., Dan M, S., Fisher, L. D., Fordyce, W. E., Hansson, T. H., Nachemson, A. L., & Wortley, M. D. (1991). A Prospective Study of Work Perceptions and Psychosocial Factors Affecting the Report of Back Injury. *Spine, 16*(1).

BJD (2008). *The burden of musculoskeletal diseases in the United States: Prevalence, societal, and economic cost*.

Bloemsaat, J. G., Meulenbroek, R. G. J., & Galen, G. P. V. (2005). Differential effects of mental load on promixal and distal arm muscle activity. *Experimental Brain Research, 167*, 622-634.

BLS (2006). *Number and incidence rate of nonfatal occupational injuries and illnesses involving days away from work by selected worker and case characteristics and musculoskeletal disorders, 2006*. Retrieved 20 July 2008. from www.bls.gov.

BLS (2008). Number and incidence rate of nonfatal occupational injuries and illnesses involving days away from work by selected worker and case characteristics and musculoskeletal disorders Retrieved Retrieved 2010 May 4, from http://www.bls.gov/news.release/pdf/osh2.pdf

BLS (2009). Number and incidence rate of nonfatal occupational injuries and illnesses involving days away from work by selected worker and case characteristics and musculoskeletal disorders Retrieved Retrieved 2011 May 4, from http://www.bls.gov/news.release/osh2.t20.htm

Boksem, M. A. S., Meijman, T. F., & Lorist, M. M. (2006). Mental fatigue, motivation and action monitoring. *Biological Psychology, 72*(2), 123-132.

Bongers, P., Ijmker, S., Van Den Heuvel, S., & Blatter, B. (2006). Epidemiology of work related neck and upper limb problems: psychosocial and personal risk factors (part I) and effective interventions from a bio behavioural perspective (part II). *Journal of Occupational Rehabilitation, 16*(3), 272-295.

Bongers, P. M., de Winter, C. R., Kompier, M. A. J., & Hildebrandt, V. H. (1993). Psychosocial factors at work and musculoskeletal disease. *Scandinavian Journal of Work Environment and Health, 19*(5), 297-312.

Borg, G. (1982). A category scale with ratio properties for intermodal and inter-individual comparisons. In H. G. Geissler & P. Petzold (Eds.), *Psychophysical Judgment and the Process of Perception* (pp. 25-34). Berlin: VEB Deutscher Verlag der Wissenschaften.

Borg, G. (1990). Psychophysical scaling with applications in physical work and the perception of exertion. *Scandinavian Journal of Work, Environment & Health, 16*, 55.

Bridges, C., Clark, B., Hammond, R., & Stephenson, L. (1991). Skeletal muscle bioenergetics during frequency-dependent fatigue. *Am J Physiol, 260*, 643-651.

Buckle, P. W. (1997). Upper limb disorders and work: the importance of physical and psychosocial factors. *Journal of Psychosomatic Research, 43*(1), 17-25.

Callister, R., Suwarno, N. O., & Seals, D. R. (1992). Sympathetic activity is influenced by task difficulty and stress perception during mental challenge in humans. *The Journal of Physiology, 454*(1), 373.

Carayon, P., Smith, M., & Haims, M. (1999). Work organization, job stress, and work-related musculoskeletal disorders. *Human Factors, 41*, 644-663.

Carter, J., & Banister, E. (1994). Musculoskeletal problems in VDT work: a review. *Ergonomics, 37*(10), 1623.

Carter, J. R., Kupiers, N. T., & Ray, C. A. (2005). Neurovascular responses to mental stress. *The Journal of Physiology, 564*(1), 321.

Chaudhuri, A., & Behan, P. O. (2000). Fatigue and basal ganglia. *Journal of the neurological sciences, 179*(1-2), 34-42.

Christou, E. A., & Carlton, L. G. (2002). Age and contraction type influence motor output variability in rapid discrete tasks *journal of Applied Physiology, 93*, 489-498.

Christou, E. A., Shinohara, M., & Enoka, R. M. (2003). Fluctuations in acceleration during voluntary contractions lead to greater impairment of movement accuracy in old adults. *Journal of Applied Physiology, 95*(1), 373.

Chuang, M., Ting, H., Otsuka, T., Sun, X., Chiu, F., Hansen, J., & Wasserman, K. (2002). Muscle deoxygenation as related to work rate. *Medicine & Science in Sports & Exercise, 34*(10), 1614.

Davis, K. G., Marras, W. S., Heaney, C. A., Waters, T. R., & Gupta, P. (2002). The impact of mental processing and pacing on spine loading. *Spine, 27*(23), 2645-2653.

De Luca, C. J. (1997). The Use of Surface Electromyography in Biomechanics. *Journal of Applied Biomechanics, 13*, 135-163.

DeStefano, D., & LeFevre, J. A. (2004). The role of working memory in mental arithmetic. *European Journal of Cognitive Psychology, 16*(3), 353-386.

Dettmers, C., Lemon, R., Stephen, K., Fink, G., & Frackowiak, R. (1996). Cerebral activation during the exertion of sustained static force in man. *Neuroreport, 7*(13), 2103.

DiDomenico, A., & Nussbaum, M. (2008). Interactive effects of physical and mental workload on subjective workload assessment. *International Journal of Industrial Ergonomics, 38*(11-12), 977-983.

Drouin, J., Valovich-mcLeod, T., Shultz, S., Gansneder, B., & Perrin, D. (2004). Reliability and validity of the Biodex system 3 pro isokinetic dynamometer velocity, torque and position measurements. *European Journal of Applied Physiology, 91*(1), 22-29.

El ahrache, K., Imbeau, D., & Farbos, B. (2006). Percentile values for determining maximum endurance times for static muscular work. *International Journal of Industrial Ergonomics, 36*(2), 99-108.

Enoka, R., Christou, E., Hunter, S., Kornatz, K., Semmler, J., Taylor, A., & Tracy, B. (2003). Mechanisms that contribute to differences in motor performance between young and old adults. *Journal of Electromyography and Kinesiology, 13*, 1-12.

Faucett, J., & Rempel, D. (1994). VDT-related musculoskeletal symptoms: interactions between work posture and psychosocial work factors. *American Journal of Industrial Medicine, 26*(5), 597-612.

Finsen, L., Sogaard, K., Jensen, C., Borg, V., & Christensen, H. (2001). Muscle activity and cardiovascular response during computer-mouse work with and without memory demands. *Ergonomics, 44*(14), 1312-1329.

Fitts, R. H. (1996). Muscle fatigue: The cellular aspects. *American Journal of Sports Medicine, 24*, S9-S13.

Flodgren, G., Crenshaw, A., Gref, M., & Fahlstrom, M. (2009). Changes in interstitial noradrenaline, trapezius muscle activity and oxygen saturation during low-load work and recovery. *European Journal of Applied Physiology*, *107*(1), 31-42.

Fridlund, A., Hatfield, M., Cottam, G., & Fowler, S. (1986). Anxiety and striate-muscle activation: Evidence from electromyographic pattern analysis. *J Abnorm Psychol, 95*, 228-236.

Galen, G. P. V., Muller, M. L. T. M., Meulenbroek, R. G. J., & Gemmert, a. A. W. A. V. (2002). Forearm EMG Response Activity During Motor Performance in Individuals Prone to Increased Stress Reactivity *American Journal of Industrial Medicine, 41*, 406-419.

Gandevia, S. C. (2001). Spinal and Supraspinal Factors in Human Muscle Fatigue. *Physiol. Rev., 81*(4), 1725-1789.

Garde, A., Laursen, B., Jørgensen, A., & Jensen, B. (2002). Effects of mental and physical demands on heart rate variability during computer work. *European journal of applied physiology, 87*(4-5), 456.

Garg, A., Hegmann, K., Schwoerer, B., & Kapellusch, J. (2002). The effect of maximum voluntary contraction on endurance times for the shoulder girdle. *International Journal of Industrial Ergonomics, 30*(2), 103-113.

Gemmert, A., & Galen, G. (1997). Stress, neuromotor noise, and human performance: A theoretical perspective. *Journal of Experimental Psychology Human Perception and Performance, 23*, 1299-1313.

Gerra, G., Zaimovic, A., Mascetti, G. G., Gardini, S., Zambelli, U., Timpano, M., Raggi, M. A., & Brambilla, F. (2001). Neuroendocrine responses to experimentally-induced psychological stress in healthy humans. *Psychoneuroendocrinology, 26*(1), 91-107.

Glasscock, N. F., Turville, K. L., Joines, S. B., & Mirka, G. A. (1999). The effect of personality type on muscle coactivation during elbow flexion. *Human Factors, 41*(1), 51-60.

Grandjean, E. (1968). Fatigue: Its physiological and psychological significance. *Ergonomics, 11*(5), 1968.

Guillot, A., Haguenauer, M., Dittmar, A., & Collet, C. (2005). Effect of a fatiguing protocol on motor imagery accuracy. *European Journal of Applied Physiology, 95*, 186-190.

Hagberg, M. (1981). Muscle endurance and surface electromyography in isometric and dynamic exercise. *Journal of Applied Physiology, 51*, 1-7.

Hagg, G. M. (1991). Static work loads and ocupational myalgia — a new explanation model. In P. A. Anderson, D. J. Hobart & J. V. Danoff (Eds.), *Electromyographical Kinesiology* (pp. 141-144). Amsterdam: Elsevier Science Publishers.

Hainaut, K., & Duchateau, J. (1989). Muscle fatigue, effects of training and disuse. *Muscle & Nerve, 12*, 660-669.

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In P. A. Hancock & N. Meshkati (Eds.), *Human Mental Workload* (pp. 139-183). Amsterdam: North-Holland.

Heiden, M., Lyskov, E., Djupsjˆbacka, M., Hellstrˆm, F., & Crenshaw, A. (2005). Effects of time pressure and precision demands during computer mouse work on muscle oxygenation and position sense. *European Journal of Applied Physiology, 94*(1), 97-106.

Hjortskov, N., Rissen, D., Blangsted, A. K., Fallentin, N., Lundberg, U., & Søgaard, K. (2004). The effect of mental stress on heart rate variability and blood pressure during computer work. *European Journal of Applied Physiology, 92*, 84-89.

Holding, D. (1983). Fatigue. In G. R. J. Hockey (Ed.), *Stress and fatigue in human performance* (pp. 145-167). New York: John Wiley and Sons Ltd.

Jensen, B., Krag, I., BronÈe, L., & Crenshaw, A. (2008). Tissue oxygenation and haemoglobin kinetics as a function of depth in two shoulder muscles differing in fibre-type composition. *International Journal of Industrial Ergonomics*.

Jensen, C., Finsen, L., Hansen, K., & Christensen, H. (1999). Upper trapezius muscle activity patterns during repetitive manual material handling and work with a computer mouse. *Journal of Electromyography and Kinesiology, 9*, 317-325.

Johansson, H., Windhorst, U., Djupsjöbacka, M., & Passatore, M. (2003). Chronic work-related myalgia. *Centre for Musculoskeletal Research, University of Gävle, Umeå, Sweden*, 1–310.

Kalsbeek, J., & Ettema, J. (1963). Scored regularity of the heart rate and the measurement of perceptual load. *Ergonomics, 6*, 306.

Kamath, M. V., & Fallen, E. L. (1993). Power spectral analysis of heart rate variability: A noninvasive signature of cardiac autonomic function. *Critical Reviews in Biomedical Engineering, 21*, 245-311.

Karasek, R., Gardell, B., & Lindell, J. (1987). Work and non-work correlates of illness and behaviour in male and female Swedish white collar workers. *Journal of Occupational Behavior, 8*(3), 187-207.

Kell, R., & Bhambhani, Y. (2006). Relationship between erector spinae static endurance and muscle oxygenation-blood volume changes in healthy and low back pain subjects. *European Journal of Applied Physiology, 96*(3), 241-248.

Kilbom, Å. (1994). Repetitive work of the upper extremeity: Part II - the scientific basis (knowledge base) for the guide. *International Journal of Industrial Ergonomics, 14*, 59-86.

Kilborn, A. (1971). Physical training in women. *Scand J Clin Lab Invest, 28(suppl)*, 119.

Krantz, G., Forsman, M., & Lundberg, U. (2004). Consistency in physiological stress responses and electromyographic activity during induced stress exposure in women and men. *Integrative physiological and behavioral science, 39*(2), 105.

Laursen, B., Jensen, B. R., Garde, A. H., & Jorgensen, A. H. (2002). Effect of mental and physical demands on muscular activity during the use of a computer mouse and a keyboard. *Scandinavian Journal of Work Environment and Health, 28*, 215-221.

Laursen, B., Jensen, B. R., & Sjogaard, G. (1998). Effect of speed and precision demands on human shoulder muscle electromyography during a repetitive task. *European Journal of Applied Physiology, 78*, 544-548.

Linnamo, V., Moritani, T., Nicol, C., & Komi, P. (2003). Motor unit activation patterns during isometric, concentric and eccentric actions at different force levels. *Journal of Electromyography and Kinesiology, 13*(1), 93-101.

Lorist, M., Kernell, D., Meijman, T., & Zijdewind, I. (2002). Motor fatigue and cognitive task performance in humans. *The Journal of Physiology, 545*(1), 313.

Luft, C. D. B., Takase, E., & Darby, D. (2009). Heart rate variability and cognitive function: Effects of physical effort. *Biological Psychology, 82*(2), 186-191.

Lundberg, U. (2002). Psychophysiology of work: Stress, gender, endocrine response, and work-related upper extremities disorders. *American Journal of Industrial Medicine, 41*, 383-392.

Lundberg, U., Elfberg, D., Melin, B., Sandsjo, L., Palmerud, G., Kadefors, R., Edstrom, M., & Parr, D. (1999). Psychophysiological stress response, muscle tension, and neck and shoulder pain among supermarket cashiers. *Journal of Occupational Health Psychology, 4*, 245-255.

Lundberg, U., Forsman, M., Zachau, G., Ekloèf, M., Palmerud, G., Melin, B., & Kadefors, R. (2002). Effects of experimentally induced mental and physical stress on motor unit recruitment in the trapezius muscle. *Work & Stress, 16*(2), 166-178.

Lundberg, U., Kadefors, R., Melin, B., Palmerud, G., Hassmen, P., Engstrom, M., & Dohns, I. E. (1994). Psychophysiological Stress and EMG Activity of the Trapezius Muscle. *International Journal of Behavioral Medicine, 1*(4), 354-370.

Luximon, A., & Goonetilleke, R. S. (2001). Simplified subjective workload assessment technique. *Ergonomics, 44*(3), 229-243.

Macdonell, C. W., & Keir, P. J. (2005). Interfering effects of the task demands of grip force and mental processing on isometric shoulder strength and muscle activity. *Ergonomics, 48*(15), 1749-1769.

Malchaire, J., Cock, N., & Vergracht, S. (2001). Review of the factors associated with musculoskeletal problems in epidemiological studies. *International Archives of Occupational and Environmental Health, 74*, 79-90.

Malik, M., Bigger, J., Camm, A., Kleiger, R., Malliani, A., Moss, A., & Schwartz, P. (1996). Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Heart rate variability: standards of measurement, physiological interpretation, and clinical use. *Circulation, 93*(5), 1043.

Marras, W. S., Davis, K. G., Heaney, C. A., Maronitis, A. B., & Allread, W. G. (2000). The Influence of Psychosocial Stress, Gender, and Personality on Mechanical Loading of the Lumbar Spine. *Spine, 25*(23), 3045-3054.

Martens, R. (1974). Arousal and motor performance. In J. Wilmore (Ed.), *Exercise and sport science review* (Vol. 2, pp. 158-188). New York: Academic Press.

Masuda, K., Masuda, T., & Sadoyama, T. (1999). Changes in surface EMG parameters during static and dynamic fatiguing contractions. *Journal of Electromyography and Kinesiology, 9*(1), 39-46.

McGorry, R., Maikala, R., Lin, J., & Rivard, A. (2009). Oxygenation kinetics of forearm muscles as a function of handle diameter during a repetitive power grip force task. *International Journal of Industrial Ergonomics, 39*(2), 465-470.

McLean, L., & Quhart, N. U. (2002). The influence of psychological stressors on myoelectrical signal activity in the shoulder region during a data entry task. *Work & Stress, 16*(2), 138-153.

Mehta, R., & Agnew, M. J. (in press). Effects of concurrent physical and mental demands for a short duration static task. *International Journal of Industrial Ergonomics*.

Melin, B., & Lundberg, U. (1997). A biopsychosocial approach to work-stress and musculoskeletal disorders. *Journal of Psychophysiology, 11*, 238-247.

Merletti, R., & Lo Conte, L. R. (1995). Advances in processing of surface myoelectric signals: Part 1. *Med. & Biol. Eng. & Comput., 33*, 362-372.

Meshkati, N. (1988). Heart rate variability and mental workload assessment. In P. A. Hancock & N. Meshkati (Eds.), *Human mental workload*. North-Holland: Elsevier Science Publishers.

Milner-Brown, H., Mellenthin, M., & Miller, R. (1986). Quantifying human muscle strength, endurance and fatigue. *Archives of physical medicine and rehabilitation, 67*(8), 530.

Norman, D. (1999). Affordance, conventions, and design. *Interactions (New York, N.Y.), 6*(3), 38.

NRC (2001). Musculoskeletal disorders and the workplace: Low back and upper extremities.

Nunnally, J. D. (1978). *Psychometric Theory* (2nd ed.). New York: McGraw-Hill.

Passatore, M., & Roatta, S. (2003). Sympathetic nervous system: Interaction with muscle function and involvement in motor control. In H. Johansson, U. Windhorst, M. Djupsjöbacka & M. Passatore (Eds.), *Chronic work-related myalgia - neuromuscular mechanisms behind work-related chronic muscle pain syndromes* (pp. 243-263). Gävle, Sweden: Gävle University Press.

Perotto, D. (1994). *Anatomical guide for the electromyographer: The limbs and trunk* (3rd ed.). Springfield, IL: Charles C. Thomas.

Petrofsky, J. S., Glaser, R. M., Phillips, C. A., Lind, A. R., & Williams, C. (1982). Evaluation of the amplitude and frequency components of the surface EMG as an index of muscle fatigue. *Ergonomics, 25*(3), 213-223.

Pot, F., Padmos, P., & Brouwers, A. (1987). Determinants of the VDU operator's wellbeing. In B. Knave & P. Wideback (Eds.), *Work with display units* (Vol. 86, pp. 16–25). Stockholm, Sweden: Elsevier Science Publishers.

Praagman, M., Veeger, H., Chadwick, E., Colier, W., & Van Der Helm, F. (2003). Muscle oxygen consumption, determined by NIRS, in relation to external force and EMG. *Journal of Biomechanics, 36*(7), 905-912.

Ranganathan, V., Siemionow, V., Sahgal, V., & Yue, G. (2001). Effects of aging on hand function. *Journal of the American Geriatrics Society, 49*(11), 1478.

Reid, G. B., & Nygren, T. E. (1988). The subjective workload assessment technique: A scaling procedure for measuring mental workload. In P. A. Hancock & N. Meshkati (Eds.), *Human Mental Workload* (pp. 185-218). Amsterdam: North Holland.

Roatta, S., Kalecik, N., & Passatore, M. (2003). Sympathetic nervous system: sensory modulation and involvement in chronic pain. In H. Johansson, U. Windhorst, M. Djupsjöbacka & M. Passatore (Eds.), *Chronic work related myalgia, neuromuscular mechanisms behind work-related chronic muscle pain syndromes* (pp. 256-276). Gävle university press, Sweden.

Rohmert, W. (1962). Fixing Rest Allowances for Static Muscular Work. *Ergonomics, 5*, 489.

Rohmert, W. (1973). Problems in determining rest allowances. *Applied Ergonomics, 4*(2), 91-95.

Rowe, J., Toni, I., Josephs, O., Frackowiak, R., & Passingham, R. (2000). The prefrontal cortex: response selection or maintenance within working memory? *Science, 288*(5471), 1656.

Rudolph, K., Axe, M., Buchanan, T., Scholz, J., & Snyder-Mackler, L. (2001). Dynamic stability in the anterior cruciate ligament deficient knee. *Knee Surgery, Sports Traumatology, Arthroscopy, 9*(2), 62-71.

Ryu, K., & Myung, R. (2005). Evaluation of mental workload with a combined measure based on physiological indices during a dual task of tracking and mental arithmetic. *International Journal of Industrial Ergonomics, 35*(11), 991-1009.

Sauter, S., Gottlieb, M., Jones, K., Dodson, V., & Rohrer, K. (1983). Job and health implications of VDT use: initial results of the Wisconsin-NIOSH study. *Commun of the ACM 26*(4), 284-294.

Sauter, S. L., & Swanson, N. G. (1996). An ecological model of musculoskeletal disorders in office work. In S. D. Moon & S. L. Sauter (Eds.), *Beyond Biomechanics: Psychosocial Aspects of Musculoskeletal Disorders in Office Work* (pp. 3-21). London: Taylor and Francis.

Schleifer, L. M., Spalding, T. W., Kerick, S. E., Cram, J. R., Ley, R., & Hatfield, B. D. (2008). Mental stress and trapezius muscle activation under psychomotor challenge: A focus on EMG gaps during computer work. *Psychophysiology, 45*(3), 356 - 365.

Sejersted, O. M., & Vollestad, N. K. (1993). Physiology of muscle fatigue and associated pain. In H. Vaeroy & H. Merskey (Eds.), *Progress in fibromyalgia and myofascial pain* (pp. 41-51). Amsterdam: Elsevier.

Silverstein, B., Welp, E., Nelson, N., & Kalat, J. (1998). Claims incidence of work-related disorders of the upper extremities: Washington state, 1987 through 1995. *American Journal of Public Health, 88*(12), 1827.

Sjogaard, G., & Jensen, B. (2006). *Low-Level Static Exertions in the Workplace*.

Sjogaard, G., Jensen, B. R., Hargens, A. R., & Sogaard, K. (2004). Intramuscular pressure and EMG relate during static contractions but dissociate with movement and fatigue. *Journal of Applied Physiology, 96*(4), 1522.

Skov, T., Borg, V., & Orhede, E. (1996). Psychosocial and physical risk factors for musculoskeletal disorders of the neck, shoulders, and lower back in salespeople. *Occupational and Environmental Medicine, 53*(5), 351-356.

Sluiter, J. K., Frings-Dresen, M. H. W., Meijman, T. F., & van der Beek, A. J. (2000). Reactivity and recovery from different types of work measured by catecholamines and cortisol: a systematic literature overview. *Occup. Environ. Med., 57*(5), 298-315.

SoGaard, K. (1995). Motor unit recruitment pattern during low level static and dynamic contractions. *Muscle & Nerve, 18*(3), 292-300.

Sommerich, C. M., McGlothlin, J. D., & Marras, W. S. (1993). Occupational risk factors associated with soft tissue disorders of the shoulder: a review of recent investigations in the literature. *Ergonomics, 36*(6), 697 - 717.

Spengler, D., Bigos, S., Martin, N., Zeh, J., Fisher, L., & Nachemson, A. (1986). Back injuries in industry: A retrospective study. I. Overview and cost. *Spine, 11*, 241-245.

Stebbins, C. L., Walser, B., & Jafarzadeh, M. (2002). Cardiovascular responses to static and dynamic contraction during comparable workloads in humans. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology, 283*(3), R568.

Tachi, M., Kouzaki, M., Kanehisa, H., & Fukunaga, T. (2004). The influence of circulatory difference on muscle oxygenation and fatigue during intermittent static dorsiflexion. *European Journal of Applied Physiology, 91*(5), 682-688.

Takala, E. (2002). Static muscular load, an increasing hazard in modern information technology. *Scand J Work Environ Health*, *28*, 211-213.

Theorell, T., Harms-Ringdahl, K., Ahlberg-Hultén, G., & Westin, B. (1991). Psychosocial job factors and symptoms from the locomotor system: a multicausal analysis. *Scand J Rehabil Med Sci Sports Exercise, 23*(3), 165-173.

Trbovich, P. L., & Lefevre, J.-A. (2003). Phonological and visual working memory in mental addition. *Memory & Cognition, 31*(5), 738-745.

van der Windt, D., Thomas, E., Pope, D., de Winter, A., Macfarlane, G., Bouter, L., & Silman, A. (2000). Occupational risk factors for shoulder pain: a systematic review. *British Medical Journal*, *57*(7), 433.

van Loon, E. M., Masters, R. S. W., Ring, C., & McIntyre, D. B. (2001). Changes in limb stiffness under conditions of mental stress. *Journal of Motor Behavior*, *33*(2), 153-164.

Vedsted, P., Blangsted, A. K., S¯gaard, K., Orizio, C., & Sj¯gaard, G. (2006). Muscle tissue oxygenation, pressure, electrical, and mechanical responses during dynamic and static voluntary contractions. *European Journal of Applied Physiology*, *96*(2), 165-177.

Veiersted, K. B. (1994). Sustained muscle tension as a risk factor for trapezius myalgia. *International Journal of Industrial Ergonomics*, *14*(4), 333-339.

Vøllestad, N. K. (1997). Measurement of human muscle fatigue. *Journal of Neuroscience Methods, 74*, 219-227.

Waersted, M. (2000). Human muscle activity related to non-biomechanical factors in the workplace. *European Journal of Applied Physiology, 83*, 151-158.

Waersted, M., Bjorklund, R. A., & Westgaard, R. H. (1991). Shoulder muscle tension induced by two VDU-based tasks of different complexity. *Ergonomics, 34*(2), 137-150.

Waersted, M., Eken, T., & Westgaard, R. H. (1996). Activity of single motor units in attention-demanding tasks: Firing pattern in the human trapezius muscle. *European Journal of Applied Physiology*, *72*, 323-329.

Waersted, M., & Westgaard, R. H. (1996). Attention-related muscle activity in different body regions during VDU work with minimal physical activity. *Ergonomics*, *39*(4), 661-676.

Wahlström, J., Hagberg, M., Johnson, P., Rempel, D., & Svensson, J. (2002). Influence of time pressure and verbal provocation on physiological and psychological reactions during work with a computer mouse. *European Journal of Applied Physiology, 87*, 257-263.

Warren, N. (2001). Work stress and musculoskeletal disorder etiology: The relative roles of psychosocial and physical risk factors. *Work: A Journal of Prevention, Assessment and Rehabilitation, 17*(3), 221-234.

Webster, B., & Snook, S. (1994). The cost of 1989 workers' compensation low back pain claims. *Spine, 19*(10), 1111.

Welford, A. T. (1973). Stress and performance. *Ergonomics*, *16*(5), 567-580.

Westgaard, R. H. (1999). Effects of physical and mental stressors on muscle pain. *Scandinavian Journal of Work Environment and Health, 25*(suppl 4), 19-24.

Westgaard, R. H., & Bjorklund, R. (1987). Generation of muscle tension additional to postural muscle load. *Ergonomics, 30*(6), 911 - 923.

WHO (1985). *Identification and control of work-related diseases : Report of a WHO expert committee.* Albany, NY: Geneva: World Health Organization.

Wickens, C. D., & Hollands, J. G. (2000). *Engineering psychology and human performance* (3 ed.). Upper Saddle River, NJ: Prentice Hall.

Yassierli, & Nussbaum, M. A. (2007). Muscle fatigue during intermittent isokinetic shoulder abduction: Age effects and utility of electromyographic measures. *Ergonomics, 50*(7), 1110-1126.

Yassierli, Nussbaum, M. A., Iridiastadi, H., & Wojcik, L. A. (2007). The influence of age on isometric endurance and fatigue is muscle dependant: a study of shoulder abduction and torso extension. *Ergonomics, 50*(1), 26-45.

Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology of Psychology, 18*, 459-482.

Yoon, T., Keller, M. L., De-Lap, B. S., Harkins, A., Lepers, R., & Hunter, S. K. (2009). Sex differences in response to cognitive stress during a fatiguing contraction. *Journal of Applied Physiology, 107*(5), 1486.

Yoshitake, Y., Ue, H., Miyazaki, M., & Moritani, T. (2001). Assessment of lower-back muscle fatigue using electromyography, mechanomyography, and near-infrared spectroscopy. *European Journal of Applied Physiology, 84*(3), 174-179.

Zago, L., Pesenti, M., Mellet , E., Crivello, F., Mazoyer, B., & Tzour io-Mazoyer, N. (2001). Neural correlations of simple and complex mental calculation. *NeuroImage, 13*, 314-327.

Zhang, Q., Andersson, G., Lindberg, L. G., & Styf, J. (2004). Muscle blood flow in response to concentric muscular activity vs. passive venous compression. *Acta Physiologica Scandinavica, 180*(1), 57-62.

Zijdewind, I., van Duinen, H., Zielman, R., & Lorist, M. (2006). Interaction between force production and cognitive performance in humans. *Clinical Neurophysiology, 117*(3), 660-667.

APPENDICES

APPENDIX A: Informed Consent Form for Study 1

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
Informed Consent for Participants in Research Projects Involving Human Subjects

Title of Project: Investigating the interactive effects of physical and mental demands on physiological responses

Investigator(s): Michael Agnew, Ranjana Mehta
Michael J. Agnew, Ph.D – Department of Industrial and Systems Engineering
Ranjana Mehta, Ph.D. Candidate – Department of Industrial and Systems Engineering

I. Purpose of this Research/Project

This study investigates potential causes of work-related musculoskeletal disorders (WMSDs) such as low back pain, shoulder injuries, carpal tunnel syndrome, etc. that may be reported from a wide variety of occupations ranging from typists to construction workers. The main objective of this study is to investigate the interactive effects of physical and mental demands on the development of WMSDs. This data collection method will allow researchers to obtain information on physical and psychosocial exposure and individual characteristics and relate this information to subsequent reports or perceived workload, discomfort, and WMSD symptoms.

II. Procedures

You will perform three experiments on three different days, with at least a week between each experiment, and an additional preliminary session. For the preliminary session, you will undergo an endurance test of your shoulder till exhaustion. For each experiment, based on the muscle group, you will be fitted with sensors that track the activity of your neck/shoulder, and upper arm, or back muscles, and oxygenation of those muscles. A gender-matched research member will assist you in placing the sensors on your back muscles, and the heart rate monitor on your chest. For two of the sessions, the task requires maintaining a constant force in one hand, these data will only be monitored for your dominant arm, and for the last session the task will require you to maintain a constant force using your back muscles. We need to record the peak strength of some of these muscles as well. This means you will have to do a series of exercises that will isolate each muscle. Following these tests and adequate rest, the study session will begin.

Before you begin each experiment, we will compute physical loads that you need to maintain using your wrist, shoulder, or torso based on low and high levels of your peak strength. For the first session, focusing on the shoulder, you will be seated in a chair with your dominant arm parallel to the floor, at shoulder level. You will be asked to grip a handle, connected to the chair, and exert and maintain a force on the handle to match a computer output relating to the level of the physical task. You will either exert a force alone, or exert the same force while performing a mental task simultaneously. You are encouraged to perform the mental task as accurately as possible while keeping your posture steady. You will repeat three trials of each treatment condition. After completing each treatment condition, you will be asked to complete a discomfort rating survey of the different body parts and provide your ratings of workload using two questionnaire based scale (i.e., Borg CR10 scale and NASA-TLX scores).

For the second session, focusing on the wrist, the procedure will be the same, but you will be seated in a chair with your elbows at 90 degrees and your lower arm strapped in an attachment. You will either exert a force alone, or exert the same force while performing a mental task simultaneously. You are encouraged to perform the mental task as accurately as possible while keeping your posture steady. You will repeat three trials of each treatment condition. After completing each treatment condition, you will be asked to complete a discomfort rating survey of the different body parts and provide your ratings of workload using two questionnaire based scale (i.e., Borg CR10 scale and NASA-TLX).

For the third session, focusing on the torso, you will be asked to stand on a platform, with your upper body inclined at 60 degrees, and an attachment fixed on your back that will measure the forces generated. Similar to the first two sessions, you will either exert a force alone, or exert the same force while performing a mental task simultaneously. You are encouraged to perform the mental task as accurately as possible while keeping your posture steady. You will repeat three trials of each treatment condition. After completing each treatment condition, you will be asked to complete a discomfort rating survey of the different body parts and provide your ratings of workload using two questionnaire based scale (i.e., Borg CR10 and NASA-TLX).

III. Risks

There is minimal risk associated with this study, no more than would be found in daily office activities. You may experience temporary discomfort or fatigue in the arms or shoulder, but as such, the potential risks associated with the study are minimal. If the discomfort becomes too great, you can stop the study at any time. Also, an investigator will be monitoring you to minimize any chance of overexertion and strain. If you are injured during the course of this study, neither the researchers nor Virginia Tech have money set aside to pay for your medical treatment. You will be personally responsible for any costs associated with any treatment you require.

IV. Benefits

By participating in this study, you will be assisting the investigators in possibly identifying factors that may contribute to the development of work-related musculoskeletal disorders in the arms or shoulders due to performing tasks under different conditions.

V. Extent of Anonymity and Confidentiality

The data from this study will be kept strictly confidential. No data will be released to anyone but the principal investigator and graduate students involved in the project without written consent of the subject. Data will be identified by subject number.

VI. Compensation

There is no compensation allotted for this study.

VII. Freedom to Withdraw

You are free to withdraw from this study at any time without penalty or reason stated, and no penalty or withholding of compensation will occur for doing so.

VIII. Subject's Responsibilities

I voluntarily agree to participate in this study. I have the following responsibilities:

1. To read and understand all instructions.
2. To work under the conditions specified by the experimenter to the best of my ability.
3. To inform the investigator of any discomforts I experience immediately.
4. Be aware that I am free to ask questions at any point.

IX. Subject's Permission

I have read the Consent Form and conditions of this project and the answers I have included within the declaration of physical health are factual. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent:

____ Date__________
Subject signature

____ Date __________
Witness (Optional except for certain classes of subjects)

Should I have any pertinent questions about this research or its conduct, and research subjects' rights, and whom to contact in the event of a research-related injury to the subject, I may contact:

Ranjana Mehta	(716) 348-1124 / rkmehta@vt.edu
Investigator(s)	Telephone/e-mail
Thurmon Lockhart, PhD	(540) 231-9088 / lockhart@vt.edu
Departmental Reviewer/Department Head	Telephone/e-mail
David M. Moore	540-231-4991/moored@vt.edu
Chair, Virginia Tech Institutional Review Board for the Protection of Human Subjects Office of Research Compliance 2000 Kraft Drive, Suite 2000 (0497) Blacksburg, VA 24060	Telephone/e-mail

APPENDIX B: Informed Consent Form for Study 2

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants in Research Projects Involving Human Subjects

Title of Project: Investigating the interactive effects of physical and mental demands on muscle activity, coactivity and joint strength for intermittent static and dynamic shoulder exertions

Investigator(s): Michael Agnew, Ranjana Mehta
Michael J. Agnew, Ph.D – Department of Industrial and Systems Engineering
Ranjana Mehta, Ph.D. Candidate – Department of Industrial and Systems Engineering

I. Purpose of this Research/Project

This study investigates potential causes of work-related musculoskeletal disorders (WMSDs) such as shoulder injuries, carpal tunnel syndrome, etc. that may be reported from a wide variety of occupations ranging from typists to construction workers. The main objective of this study is to investigate the interactive effects of physical and mental demands on the development of WMSDs. This data collection method will allow researchers to obtain information on physical and psychosocial exposure and individual characteristics and relate this information to subsequent reports or perceived workload, discomfort, and WMSD symptoms.

II. Procedures

You will attend three sessions: One preliminary and two experimental sessions. On the experimental session, you will be fitted with sensors that track the activity of your neck/shoulder. A gender-matched research member will assist you to place the heart rate monitor on your chest. The task requires maintaining a constant force in one hand, these data will only be monitored for your dominant arm. We need to record the peak strength of some of these muscles as well. This means you will have to do a series of exercises that will isolate each muscle. Following these tests and adequate rest, the study session will begin.

Before you begin each experiment, we will compute physical loads that you need to maintain using your shoulder based on low and high levels of your peak strength. You will be seated in a chair with your dominant arm parallel to the floor, at shoulder level. You will be asked to grip a handle, connected to the chair, and exert a force on the handle to match a computer output relating to the level of the physical task, while moving your arm from your side to a horizontal level, and back to the side within 5 seconds. You will either exert a force alone, or exert the same force while performing a mental task simultaneously. You will rest for the next 5 seconds, after which you will perform the same exertion and rest for 3 minutes. You are encouraged to perform the mental task as accurately as possible while performing the dynamic task. After completing each treatment condition, you will be asked to complete a discomfort rating survey of the different body parts and provide your ratings of workload using a questionnaire based scale (NASA-TLX).

III. Risks

There is minimal risk associated with this study, no more than would be found in daily office activities. You may experience temporary discomfort or fatigue in the arms or shoulder, but as such, the potential risks associated with the study are minimal. If the discomfort becomes too great, you can stop the study at any time. Also, an investigator will be monitoring you to minimize any chance of overexertion and strain. If you are injured during the course of this study, neither the researchers nor Virginia Tech have money set aside to pay for your medical treatment. You will be personally responsible for any costs associated with any treatment you require.

IV. Benefits

By participating in this study, you will be assisting the investigators in possibly identifying factors that may contribute to the development of work-related musculoskeletal disorders in the arms or shoulders due to performing tasks under different conditions.

V. Extent of Anonymity and Confidentiality

The data from this study will be kept strictly confidential. No data will be released to anyone but the principal investigator and graduate students involved in the project without written consent of the subject. Data will be identified by subject number.

VI. Compensation

There is no compensation allotted for this study.

VII. Freedom to Withdraw

You are free to withdraw from this study at any time without penalty or reason stated, and no penalty or withholding of compensation will occur for doing so.

VIII. Subject's Responsibilities

I voluntarily agree to participate in this study. I have the following responsibilities:

1. To read and understand all instructions.
2. To work under the conditions specified by the experimenter to the best of my ability.
3. To inform the investigator of any discomforts I experience immediately.
4. Be aware that I am free to ask questions at any point.

IX. Subject's Permission

I have read the Consent Form and conditions of this project and the answers I have included within the declaration of physical health are factual. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent:

____ Date__________
Subject signature

____ Date __________
Witness (Optional except for certain classes of subjects)

Should I have any pertinent questions about this research or its conduct, and research subjects' rights, and whom to contact in the event of a research-related injury to the subject, I may contact:

Ranjana Mehta	(716) 348-1124 / rkmehta@vt.edu
Investigator(s)	Telephone/e-mail

Thurmon Lockhart, PhD	(540) 231-9088 / lockhart@vt.edu
Departmental Reviewer/Department Head	Telephone/e-mail
David M. Moore	540-231-4991/moored@vt.edu
Chair, Virginia Tech Institutional Review Board for the Protection of Human Subjects Office of Research Compliance 2000 Kraft Drive, Suite 2000 (0497) Blacksburg, VA 24060	Telephone/e-mail

APPENDIX C: Informed Consent Form for Study 3

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants in Research Projects Involving Human Subjects

Title of Project: Investigating the interactive effects of physical and mental demands on muscle endurance and capacity

Investigator(s): Michael Agnew, Ranjana Mehta
Michael J. Agnew, Ph.D – Department of Industrial and Systems Engineering
Ranjana Mehta, Ph.D. Candidate – Department of Industrial and Systems Engineering

I. Purpose of this Research/Project

This study investigates potential causes of work-related musculoskeletal disorders (WMSDs) such as shoulder injuries, carpal tunnel syndrome, etc. that may be reported from a wide variety of occupations ranging from typists to construction workers. The main objective of this study is to investigate the interactive effects of physical and mental demands on the development of WMSDs. This data collection method will allow researchers to obtain information on physical and psychosocial exposure and individual characteristics and relate this information to subsequent reports or perceived workload, discomfort, and WMSD symptoms.

II. Procedures

You will attend seven sessions: One preliminary and six experimental sessions. On the experimental session, you will be fitted with sensors that track the activity of your neck/shoulder. A gender-matched research member will assist you to place the heart rate monitor on your chest. The task requires maintaining a constant force in one hand, these data will only be monitored for your dominant arm. We need to record the peak strength of some of these muscles as well. This means you will have to do a series of exercises that will isolate each muscle. Following these tests and adequate rest, the study session will begin.

Before you begin each experiment, we will compute physical loads that you need to maintain using your shoulder based on low and high levels of your peak strength. You will be seated in a chair with your dominant arm parallel to the floor, at shoulder level. You will be asked to grip a handle, connected to the chair, and exert a force on the handle to match a computer output relating to the level of the physical task for 15 seconds. You will either exert a force alone, or exert the same force while performing a mental task simultaneously. You will rest for the next 15 seconds, after which you will perform the same exertion and rest till exhaustion. You are encouraged to perform the mental task as accurately as possible while performing the static task. You will be asked to complete a discomfort rating survey of the shoulder and provide your ratings of workload using a questionnaire based scale (SWAT) intermittently. Additionally, you will be asked to fill out a questionnaire before and after the endurance test (SOFI).
A 30-minute recovery will be provided, in which you will perform maximum shoulder exertion intermittently to monitor strength recovery.

III. Risks

There is minimal risk associated with this study, no more than would be found in daily office activities. You may experience temporary discomfort or fatigue in the arms or shoulder, but as such, the potential risks associated with the study are minimal. If the discomfort becomes too great, you can stop the study at any time. Also, an investigator will be monitoring you to minimize any chance of overexertion and strain. If you are injured during the course of this study, neither the researchers nor Virginia Tech have money set aside to pay for your medical treatment. You will be personally responsible for any costs associated with any treatment you require.

IV. Benefits

By participating in this study, you will be assisting the investigators in possibly identifying factors that may contribute to the development of work-related musculoskeletal disorders in the arms or shoulders due to performing tasks under different conditions.

V. Extent of Anonymity and Confidentiality

The data from this study will be kept strictly confidential. No data will be released to anyone but the principal investigator and graduate students involved in the project without written consent of the subject. Data will be identified by subject number.

VI. Compensation

There is no compensation allotted for this study.

VII. Freedom to Withdraw

You are free to withdraw from this study at any time without penalty or reason stated, and no penalty or withholding of compensation will occur for doing so.

VIII. Subject's Responsibilities

I voluntarily agree to participate in this study. I have the following responsibilities:

1. To read and understand all instructions.
2. To work under the conditions specified by the experimenter to the best of my ability.
3. To inform the investigator of any discomforts I experience immediately.
4. Be aware that I am free to ask questions at any point.

IX. Subject's Permission

I have read the Consent Form and conditions of this project and the answers I have included within the declaration of physical health are factual. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent:

____ Date__________
Subject signature

____ Date __________
Witness (Optional except for certain classes of subjects)

Should I have any pertinent questions about this research or its conduct, and research subjects' rights, and whom to contact in the event of a research-related injury to the subject, I may contact:

Ranjana Mehta	(716) 348-1124 / rkmehta@vt.edu
Investigator(s)	Telephone/e-mail

Thurmon Lockhart, PhD (540) 231-9088 / lockhart@vt.edu
Departmental Reviewer/Department Head Telephone/e-mail

David M. Moore 540-231-4991/moored@vt.edu
Chair, Virginia Tech Institutional Review Telephone/e-mail
Board for the Protection of Human Subjects
Office of Research Compliance
2000 Kraft Drive, Suite 2000 (0497)
Blacksburg, VA 24060

APPENDIX D: Borg CR10 Perceived Exertion Scale

The purpose of the following list is designed to evaluate the local body part exertion during the tasks. Please fill out the blank with the best estimate of exertion level based on the scale list on the right for each body part: Hand, Lower arm, Upper arm, Shoulder, Upper back, Lower back.

0	Nothing at all
0.5	Extremely weak (just noticeable)
1	Very weak
2	Weak (light)
3	Moderate
4	Somewhat strong
5	Strong (heavy)
6	
7	Very strong
8	
9	
10	Extremely strong (almost max)

APPENDIX E: NASA-TLX Workload Scale

Refer to these descriptions as you complete the Workload Rating sheet.

Mental Demand: *Low/High* How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Physical Demand: *Low/High* How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Temporal Demand: *Low/High* How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

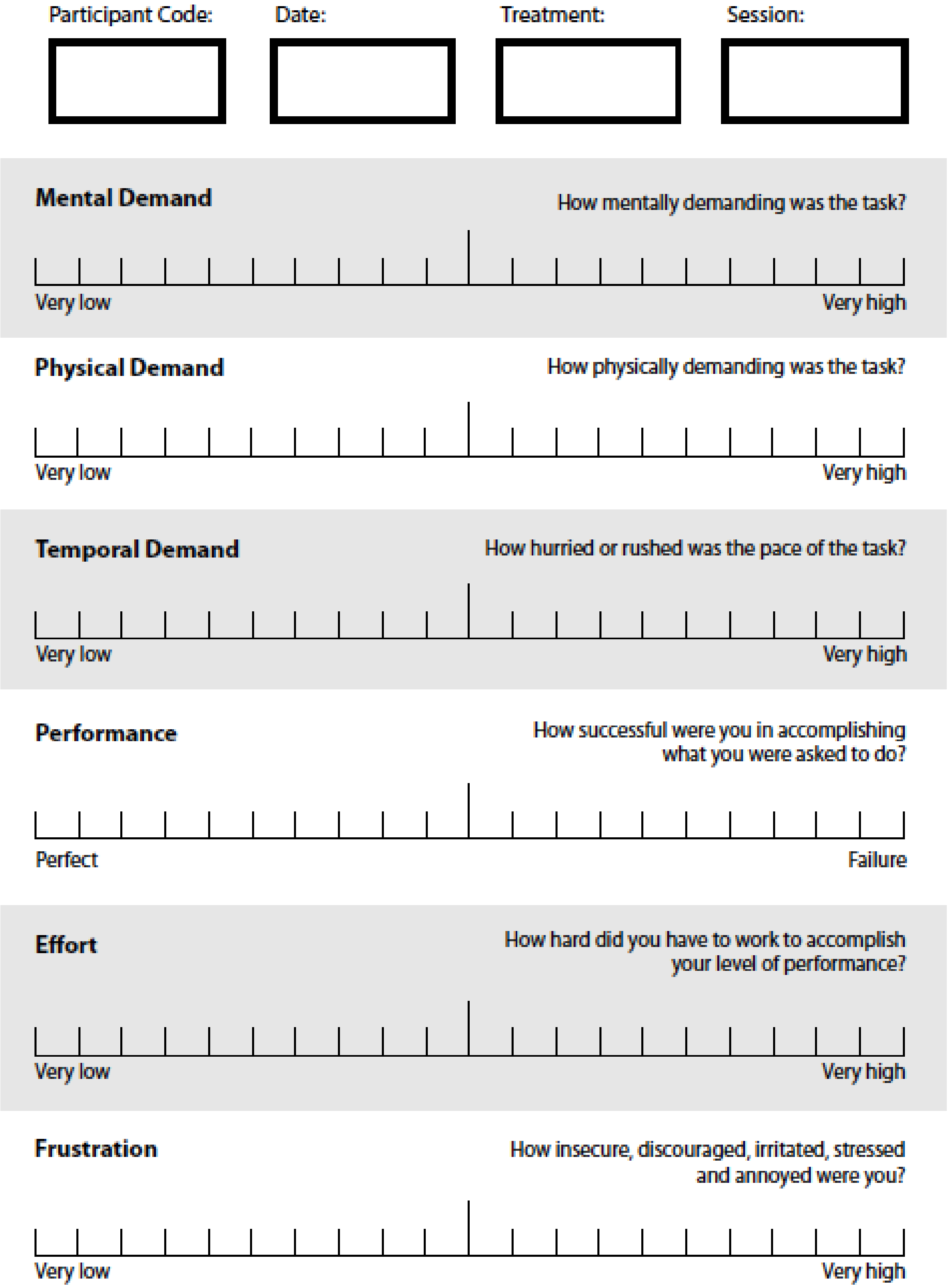
Performance: *Excellent/Poor* How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

Effort: *Low/High* How hard did you have to work (mentally and physically) to accomplish your level of performance?

Frustration Level: *Low/High* How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent did you feel during the task?

Participant Code:

Experimental Session: **Treatment Condition:**



Participant Code: Date: Treatment: Session:

Mental Demand How mentally demanding was the task?

Very low Very high

Physical Demand How physically demanding was the task?

Very low Very high

Temporal Demand How hurried or rushed was the pace of the task?

Very low Very high

Performance How successful were you in accomplishing what you were asked to do?

Perfect Failure

Effort How hard did you have to work to accomplish your level of performance?

Very low Very high

Frustration How insecure, discouraged, irritated, stressed and annoyed were you?

Very low Very high

Weights

In each pair of factors below, which of the two do you think is more important for the task that you just performed?

Place an "X" mark next to the one you think is more important than the other.

Mental Demand ☐ ☐ Physical Demand

Physical Demand ☐ ☐ Temporal Demand

Effort ☐ ☐ Performance

Frustration Level ☐ ☐ Performance

Mental Demand ☐ ☐ Effort

Effort ☐ ☐ Physical Demand

Frustration Level ☐ ☐ Mental Demand

Mental Demand ☐ ☐ Temporal Demand

Effort ☐ ☐ Frustration Level

Physical Demand ☐ ☐ Performance

Temporal Demand ☐ ☐ Effort

Mental Demand ☐ ☐ Performance

Physical Demand ☐ ☐ Frustration Level

Performance ☐ ☐ Temporal Demand

Temporal Demand ☐ ☐ Frustration Level

APPENDIX F: Swedish Occupational Fatigue Inventory

Directions: Think of how you feel right now. To what extent do the expressions below describe how you feel? For every expression, answer spontaneously, and mark the number that corresponds to how you feel right now. The numbers vary between 0 (not at all) and 6 (to a very high degree).

	None At All						**Very High Level**
palpitations	0	1	2	3	4	5	6
lack of concern	0	1	2	3	4	5	6
worn out	0	1	2	3	4	5	6
tense muscles	0	1	2	3	4	5	6
falling asleep	0	1	2	3	4	5	6
numbness	0	1	2	3	4	5	6
sweaty	0	1	2	3	4	5	6
spent	0	1	2	3	4	5	6
drowsy	0	1	2	3	4	5	6
passive	0	1	2	3	4	5	6
stiff joints	0	1	2	3	4	5	6
indifferent	0	1	2	3	4	5	6
out of breath	0	1	2	3	4	5	6
yawning	0	1	2	3	4	5	6
drained	0	1	2	3	4	5	6
sleepy	0	1	2	3	4	5	6
overworked	0	1	2	3	4	5	6
aching	0	1	2	3	4	5	6
breathing heavily	0	1	2	3	4	5	6
uninterested	0	1	2	3	4	5	6

APPENDIX G: Subjective Workload Assessment technique (SWAT)

Often have spare time. Interruptions or overlap among activities occur **infrequently or not at all**	**Occasionally** have spare time. Interruptions or overlap among activities occur **frequently**	**Almost never** have spare time. Interruptions or overlap among activities are **very frequently,** or **occur all the time**

Very little conscious mental effort or concentration required. Activity is almost automatic, requiring **little or no attention**	**Moderate** conscious mental effort or concentration required. Complexity of activity is **moderately high** due to uncertainty or unfamiliarity. **Considerable attention** required	**Extensive** mental effort or concentration required. Very complex activity requiring **total attention**

Little confusion, risk, frustration, or anxiety exists an can be **easily** accommodated	**Moderate stress** due to confusion, risk, frustration, or anxiety noticeably adds to workload. **Significant compensation** is required to maintain adequate performance	**High to very intense stress** due to confusion, frustration, or anxiety **High to extreme** determination and self-control required