

©Copyright 2012

Jeong Ho Kim

Non-invasive Real-time Assessment of Muscle Fatigue during Computer Use:
Using Mouse Button-Click and Keystroke Durations.

Jeong Ho Kim

A dissertation
submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy

University of Washington

2012

Reading Committee:

Peter W Johnson, Chair

Christina M Mastrangelo

Linda Ng Bolye

Program Authorized to Offer Degree:
Industrial and Systems Engineering

University of Washington

Abstract

Non-invasive Real-time Assessment of Muscle Fatigue during Computer Use:
Using Mouse Button-Click and Keystroke Durations.

Jeong Ho Kim

Chair of the Supervisory Committee:
Associate Professor Peter W. Johnson
Environmental and Occupational Health Sciences
Industrial and Systems Engineering

Musculoskeletal disorders (MSDs) account for a large proportion of occupational injuries. As the computer has become ubiquitous in office work environments, so have computer-related MSDs. Since most work-related MSDs develop from the accumulation of micro trauma over moderate to long periods of time, early detection of physiological degradation, i.e. muscle fatigue, may help reduce the occurrence of MSDs. There are several laboratory-based assessment tools to measure muscle fatigue; however, due to their invasiveness, lack of portability and cost, these measurement tools may not be appropriate for measuring computer-related muscle fatigue in field-based or occupational settings. Some previous studies have shown that keystroke and mouse button-click durations may be influenced by muscle fatigue or physical load. Therefore, in the present study, I investigated whether the keystroke and mouse button-click durations were sensitive enough to indicate early stages of muscle fatigue development. Since keystroke and mouse button-click durations can be readily and non-invasively measured in real-time with simple computer monitoring software while subjects do their actual work, we may be able use a non-invasive computer monitoring software program to proactively detect when computer operators may

be developing muscle fatigue which may be a precursor to the onset and development of a computer related MSD.

TABLE OF CONTENTS

	Page
List of Figures	iii
Chapter 1 - Introduction and Background	1
1.1. Computer Use and Musculoskeletal disorders	1
1.1.1 Characteristics of Computer Use.....	4
1.1.2 Populations at risk	8
1.2. Muscle fatigue	9
1.2.1 Central fatigue	11
1.2.2 Peripheral fatigue.....	12
1.3. Research objectives and overview	22
Chapter 2 - Validation of computer interaction monitoring program.....	27
2.1. Introduction	28
2.2. Methods	29
2.2.1 Subjects.....	29
2.2.2 Experimental design	30
2.2.3 Data analysis.....	31
2.3. Results	32
2.4. Discussion	33
Chapter 3 - Viability of Using Digital Signals from the Keyboard to Capture Typing Force Exposures.....	36
3.1. Introduction	37
3.2. Methods	40
3.2.1 Subjects.....	40
3.2.2 Experimental design	40
3.2.3 Data analysis.....	43
3.3. Results	44
3.3.1 Software-based measures	44
3.3.2 Force-based measures.....	44
3.3.3 Difference between software and force-based measures.....	46
3.3.4 Typing forces.....	47
3.4. Discussion	49

Chapter 4 - Viability of using keystroke and mouse button-click durations to measure muscle fatigue	54
4.1. Introduction	55
4.2. Methods	58
4.2.1 Subjects.....	58
4.2.2 Study design	58
4.2.3 Data analysis.....	69
4.3. Results	70
4.3.1 Control Condition.....	70
4.3.2 Keyboard use	72
4.3.3 Mouse use	72
4.3.4 Keyboard and Mouse use	73
4.4. Discussion	75
4.4.1 Control condition.....	75
4.4.2 Keyboard use	77
4.4.3 Mouse use.....	78
4.4.4 Keyboard and mouse use.....	79
4.4.5 Conclusion.....	81
Chapter 5 - Conclusions and future work	83
5.1. Summary	83
5.2. Contributions.....	86
5.3. Limitations	88
References.....	90
Appendix A. Recruitment E-mail (Chapter 2 and 4)	100
Appendix B. Recruitment E-mail (Chapter 3)	101
Appendix C. Subject consent form	102
Appendix D. Questionnaire for measuring peripheral fatigue (Chapter 4)	105
Appendix E. Questionnaire for measuring central fatigue (Chapter 4)	106

LIST OF FIGURES

Figure Number	Page
Figure 1.1 The number and proportion of MSDs among the total occupational injuries and illnesses: (a) total number of injury and illness cases involving days away from work compared to the percentage of MSDs cases involving days away from work (1992-2009), (b) proportion of MSDs among the total injuries in 2010. Source: Bureau of Labor Statistics.	2
Figure 1.2 Median days away from work and incidence rate due to injuries and illnesses by event or exposure in 2010. Source: Bureau of Labor Statistics.	3
Figure 1.3 Computer use and MSDs.	7
Figure 1.4 Risk estimate between computer use and MSDs. (Ijmker et al., 2007).	8
Figure 1.5 The two types and sources of muscle fatigue.	10
Figure 1.6 Excitation - Contraction coupling (Silverthorn, 2007).	15
Figure 1.7 Measurement of muscle fatigue at macro and micro levels.	18
Figure 1.8 Schematic representation of muscle fatigue (a): fresh (0), potentiated (1), potentiated and fatigued (3) and fatigued (4) muscle twitch. The corresponding digital signals measured from the mouse button or keyboard presented to visualize the hypothesis	21
Figure 1.9 Relationships between muscle twitch duration and keystroke durations. Twitch duration is the sum of contraction time and 1/2 relaxation time. The exercise duration was 15 minutes: the static exercise was sustained isometric contraction (constant force) at 15% MVC; the dynamic exercise was fluctuating force exercise (alternating between 200 milliseconds (ms) of 0% MVC and 200 ms of 30% MVC) (Chang et al., 2009)	24
Figure 2.1 The configuration of measurement systems including the external USB logger and software program.	30
Figure 2.2 Comparison of external-logger-based and software-based keystroke durations: (a) the differences in keystroke durations between the external USB logger and software program; (b) a linear fit and correlation between the two different measures. Asterisk denotes statistical significance ($p < 0.05$). The dotted line is the identity line. [$n = 17$]	32
Figure 2.3 The differences in keystroke durations between the external USB logger and software program across the eight measurement times. [$n = 17$]	33
Figure 3.1 Force-displacement curves of three keyboards: 1.8, 2.0, and 4.0 mm. The solid dots indicate the activation forces (make point) and the dashed lines the travel distances. $T_{1.8}$, $T_{2.0}$, and $T_{4.0}$ are the distances between the beginning and the end of key travel for 1.8, 2.0, and 4.0 mm keyboards, respectively.	41
Figure 3.2 Experimental setup and schematic comparisons of the measurement methods: the red and blue solid line represents the force profile and digital signal of an individual keystroke, respectively.	42
Figure 3.3 Comparisons of software-based keystroke durations [$n = 13$]: (a) by hand; (b) by finger and hand; (e) by finger and keyboard. Comparisons of force-based keystroke durations:	

(c) by hand; (d) by finger and hand; (f) by finger and keyboard. Asterisks denote statistical significance ($p < 0.05$).	45
Figure 3.4 Comparisons of software- and force-based keystroke durations [$n = 13$]: (a) the differences in the two measures grouped by keyboard; (b-c) linear fits and correlations between the keystroke durations measured from digital signals (software) and applied finger forces (force platform) on 1.8, 2.0, and 4.0 mm keyboard, respectively. The numbers on regression plots (b-c) represent subjects. Asterisks denote statistical significance ($p < 0.05$). The dotted red lines are the identity lines.	47
Figure 3.5 Comparisons of mean keystroke forces [$n=13$]: (a) by keyboard and by hand; (b) by hand and keyboard; (c) by finger and hand; (d) by finger and keyboard. Asterisks denote statistical significance ($p < 0.05$).	48
Figure 4.1 To visualize the hypothesis, schematic representation of muscle fatigue: (a) involuntary muscle twitch contractions - fresh (stage 0), potentiated (stage 1), potentiated and fatigued (stage 2) and fatigued (stage 3) muscle twitch; (b) the corresponding voluntary muscle contractions measured with the digital signals from the mouse button or keyboard presented; (c) hypothetical changes in muscle twitch force, twitch duration, and digital signal durations of keystrokes and mouse button clicks.	57
Figure 4.2 Experiment design: (a) control condition, (b) keyboard exposure condition, (c) mouse exposure condition, and (d) the combined mouse and keyboard condition. At the beginning of the experiment, during the breaks and in a two-hour recovery period, the force response of the muscle was measured (ES), a standardized omni-directional pointing task was performed with the mouse (PT), a standardized typing task was performed with the keyboard (TT), a finger tapping task was conducted with the middle finger (FT) and self-reported their peripheral muscle fatigue (PF) and boredom/central fatigue (CF).	61
Figure 4.3 Schematic representation of the omni-directional pointing task	64
Figure 4.4 Diagram of the twitch measurement apparatus as seen from the side and twitch force measure: (a) surface electrodes over FDS; (b) force transducer over the middle finger; (c) electrical stimulator; (d) restraining jig; (e) twitch force profile – F(twitch force), CT(contraction time), and $\frac{1}{2}$ RT(one-half relaxation time). Inserts show the electrical stimulation and the resultant muscle twitch. Modified with permission from Johnson (1998).	66
Figure 4.5 Design of the combined keyboard and mouse use	68
Figure 4.6 Changes in keystroke, mouse button-click, finger tapping durations (voluntary contractions), and muscle twitch durations (involuntary contractions) and the muscle twitch forces in the four different conditions [$n = 18$]. Red shaded columns indicate 75-minute blocks of exposure time (keyboard and/or mouse use), white columns indicate the rest time between blocks (15, 30, and 15 minutes respectively) and the green shaded columns indicate the two-hour recovery period. All the values normalized by the initial values at time 0. Asterisks denote statistical significance ($p < 0.05$). The standard error bars are excluded for clarity.	71
Figure 4.7 Changes subjective peripheral and central fatigue measures [$n = 18$]. Shaded columns (red) indicate 75-minute blocks of exposure time (keyboard or mouse use), the rest time between the blocks were 15, 30, and 15 minutes respectively including two hours of	

recovery (green shaded) at the end after keyboard use had ceased. Asterisks denote statistical significance at $\alpha = 0.05$. The standard error bars are excluded for the clarification..... 74

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to Dr. Peter Johnson at the University of Washington for his invaluable guidance, support, intellectual stimulation, and encouragement which has made this dissertation possible. Your passion towards research has greatly motivated me and I truly respect you and your work. It has been my great honor and pleasure to work with you and be your student.

I am deeply indebted to Dr. Linda Boyle for her tremendous feedback and support during my research. Her thoughtful feedback on this dissertation has ensured the quality of my work. I would also like to thank Dr. Christina Mastrangelo at the University of Washington for her encouragement and support during my PhD program. My teaching experience and discussions with her have greatly influenced my teaching and research philosophy. I would like to thank Dr. Peter Hoff for providing me advice on statistics and agreeing to be the GSR in my committee.

Lastly, I would like to thank my colleagues, who I have worked with at the Ergonomics Laboratory, Ryan Blood, Charlotte Lewis, Erin Hughes, Patrik Rynell, Ornwipa Thamsuwan, and Lovenoor Aulck for their unstinted support and encouragement throughout my graduate study. Their encouragement and collegueship were almost essential ingredients for this dissertation.

My research in ergonomics was supported by NIOSH R21grant (OH009088-02), Washington State Medical Aid and Accident Fund, and a research grant from the Ergonomic Research and Development Group within Hewlett-Packard.

DEDICATION

To my wife and two sons

Sae Hee Kim

Ethan Kim

Anthony Kim

Also, to my and my wife's parents

Jae Hoon Kim

Soon Hee Choi

Jeong Soo Kim

Hyo Jin Oh

This dissertation would not have been possible if it was not for your support.

Chapter 1 - Introduction and Background

1.1. Computer Use and Musculoskeletal disorders

During the last few decades, computers have become popular and almost essential for many individuals (Andries, Smulders, & Dhondt, 2002; Mikkelsen et al., 2007). According to the 2009 US Census, approximately 80.5% of people in the US, ages 15 and older, use computers at either their home or work on a daily basis. Around 68.7 % of the US households have internet access in their homes (US Bureau of the Census, 2009). About 85 million personal computers were being used in Germany, France, and the UK in 2003 (F. Gerr, Monteilh, & Marcus, 2006). While the prevalence of computers has had a positive impact on our life, previous studies (Chang, Johnson, Katz, Eisen, & Dennerlein, 2009; Fredric Gerr et al., 2002; Lassen et al., 2004) have shown that computer work may be associated with adverse health effects such as musculoskeletal disorders (MSDs) and in more severe cases, nerve entrapment disorders such as carpal tunnel syndrome.

Although computers can contribute to MSDs in the upper extremities, the causal pathways have not been well established due to the multifaceted nature of MSDs. MSDs are generally defined as inflammatory and degenerative conditions affecting the muscles, tendons, ligaments, joints, peripheral nerves, and supporting blood vessels (Punnett & Wegman, 2004). Most work-related MSDs develop from the accumulation of micro trauma to the soft tissues (muscles, tendons, ligaments and nerves) over time and often occur in the low back, neck, shoulder, forearm and hand (Punnett & Wegman, 2004). The risk factors for MSDs include physical factors such as force, duration, repetitiveness, and posture; work organizational factors such as job control, stress and relationship with co-workers; and

individual characteristics such as age, gender, work habits, health status and outside of work activities (S. Ijmker et al., 2007; Peter Wallace Johnson, 1998; Tayyari & Smith, 1997).

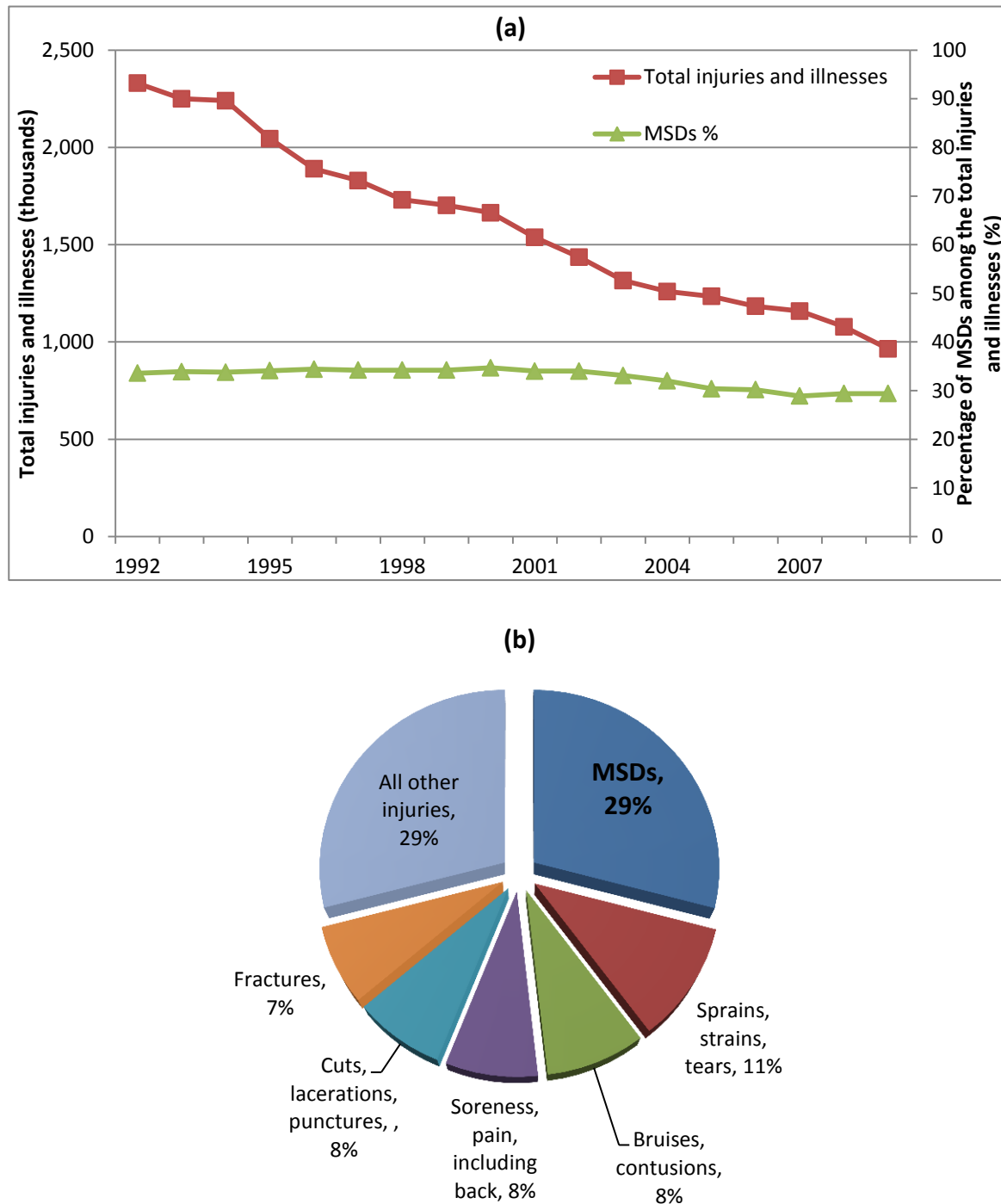


Figure 1.1 The number and proportion of MSDs among the total occupational injuries and illnesses: (a) total number of injury and illness cases involving days away from work compared to the percentage of MSDs cases involving days away from work (1992-2009), (b) proportion of MSDs among the total injuries in 2010. Source: Bureau of Labor Statistics.

Since 1992, the total number of occupational injuries and illnesses has been decreasing due to various interventions whereas the proportion of MSDs in the working population has remained relatively constant (Figure 1.1(a)). Despite the decreasing trend in occupational injuries, MSDs still are the single largest component of all injuries and illnesses, accounting for around 1/3 of total occupational injuries and illnesses in the US (Punnett & Wegman, 2004). Furthermore, MSDs are the most costly and severe types of disorders in office work environments (Lyon, 1992). According to the Bureau of Labor Statistics (Figure 1.2), the median number of days away from work due to MSD-related injuries were three times longer (24 days) than the industry average for all the other types of injuries (8 days), indicating that once an individual was injured, it would take longer time to recover from MSDs.

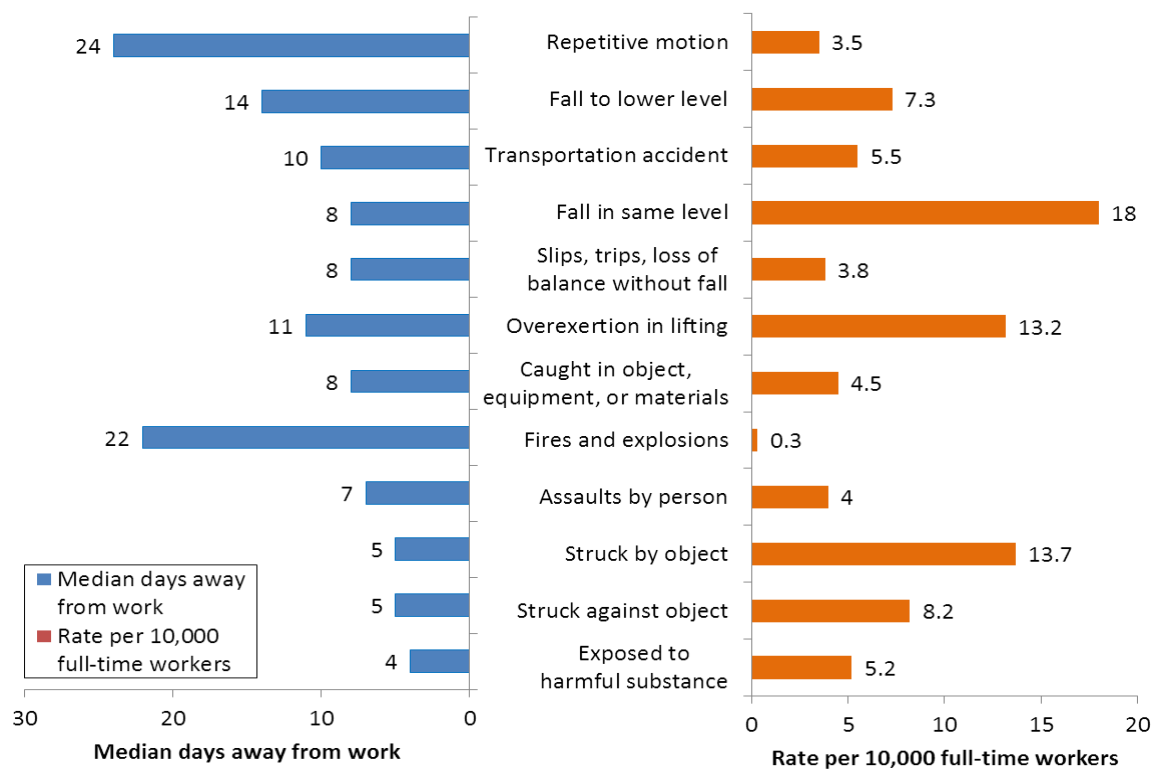


Figure 1.2 Median days away from work and incidence rate due to injuries and illnesses by event or exposure in 2010. Source: Bureau of Labor Statistics.

The increase in the number of MSDs cases among office workers has corresponded with the increasing trend of computer use. As a result, a significant proportion of the work-related MSDs in office workers may be due to intensive computer use. Previous epidemiologic studies have found that 24 to 44% of office workers are experiencing MSD-related symptoms in their hands, arms, shoulder and neck (Jensen, 2003; Juul-Kristensen, Sogaard, Stroyer, & Jensen, 2004; Lassen et al., 2004). Computer work, due to the intensive use of the finger and wrist muscles, could especially lead to soft tissue injuries on the extensor and flexor muscles in the forearm (Pascarelli & Kella, 1993; Rose, 1991). Therefore, it is important to understand the association between computer use and MSDs in the upper extremities: especially with respect to the forearm muscles which power our fingers, hands and wrists. To better understand these associations, an important place to start is to understand how computers are typically used.

1.1.1 Characteristics of Computer Use

Computer work time can be characterized by the duration of the work, patterns of input device use (e.g. mouse and keyboard) and the duration and patterns of the idle periods, inactivity or rest. The characterization of computer activity and inactivity is essential for understanding the association between the computer use and MSDs. In the following sections, the characteristics of computer use in terms of duration, patterns of input device use and the duration and patterns of inactivity are described in order to better understand how computer use may contribute to the onset and development of upper extremity MSDs.

1.1.1.1 Duration of Computer Use

Epidemiological studies have shown that musculoskeletal discomfort and injuries are positively associated with duration of computer use (Blatter & Bongers, 2002; Bongers,

Ijmker, van den Heuvel, & Blatter, 2006; S. Ijmker et al., 2008). In other words, as the duration of computer use increases, the computer operator's likelihood to develop MSDs increases (Andries et al., 2002). Therefore, investigating factors surrounding the duration of computer use and the potential adverse health effects is a logical starting point. According to previous studies (Andries et al., 2002; Burke & Peper, 2002; Chang et al., 2007; Heinrich, Blatter, & Bongers, 2004; Mikkelsen et al., 2007), the average duration of computer use is approximately 2 hours/day (hr/day), ranging from 2.0 to 2.5 hr/day with standard deviations ranging from 0.96 to 1.4 hr/day. These studies have consistently found that 2.0-2.5 hours of daily computer use is long enough to increase the risk of MSDs.

1.1.1.2 Measurement of computer use duration

There are two main types of measurement methods used in the literature to measure computer work: subjective and objective measurement methods. Most of the early studies on computer usage utilized subjective measurement methods. Typical subjective methods included questionnaires and observations. Researchers often chose questionnaires because they were relatively inexpensive, relatively large amounts of data could be collected, and the data was relatively simple to analyze. Due to the subjective nature of the data, however, study results could be biased or unreliable depending upon the design of the data collection tools or how respondents perceived and answered questions. Some previous studies (Heinrich et al., 2004; Mikkelsen et al., 2007) have shown that people tend to overestimate their computer usage time; that is, the subjective self-reported measures of computer use durations are often longer than and are overestimates relative to the objective measures.

Van Eerd et al., (2009) showed that direct observations are more reliable than self-reported questionnaires. However, the direct observations have significant disadvantages.

The reliability of the measures from direct observations depends heavily on the ability of the trained observer because the identification of tasks and time interacting with the computer varies depending on the observer's perceptions. Furthermore, one of the biggest limitations of direct observations is the *Hawthorne effect*; i.e. when people are aware of the observation, their behaviors might change (Clayton & Griffith, 2004). This Hawthorne effect could have a significant impact on the representativeness of the collected data. In addition, since direct observation is costly, it is not the appropriate method for studies with large sample sizes or longitudinal studies.

A more preferable, objective method for characterizing computer use, either with large samples or over long periods of time, is monitoring computer activity using software installed on the subject's own computer. Some studies (Heinrich et al., 2004; Mikkelsen et al., 2007) have utilized a commercially-available program called WorkPace Recorder (Niche Software Ltd, ErgoDirect, New Zealand) whereas other studies (Chang et al., 2007; Richter, Slijper, Over, & Frens, 2008) have used custom programs created by the investigators themselves. These software programs enable researchers to collect a large amount of objective computer use data with relatively low costs since software programs can be easily distributed and installed in many different computers.

1.1.1.3 Patterns of computer use

As mentioned earlier, computer use can be characterized by duration of keyboard and mouse use and duration of inactivity or rest. Keyboard use is a complicated and consists of highly repetitive and dynamic muscle movements (Chang et al., 2009). Although a typing task typically requires only 5% of a subject's maximal strength on average, as shown in Figure 1.3, the repetitive movements may induce muscle fatigue or change physiological

performance of the forearm muscles (Chang et al., 2009). Gerr et al. (2002) showed that computer keyboard use is associated with upper extremity MSDs.

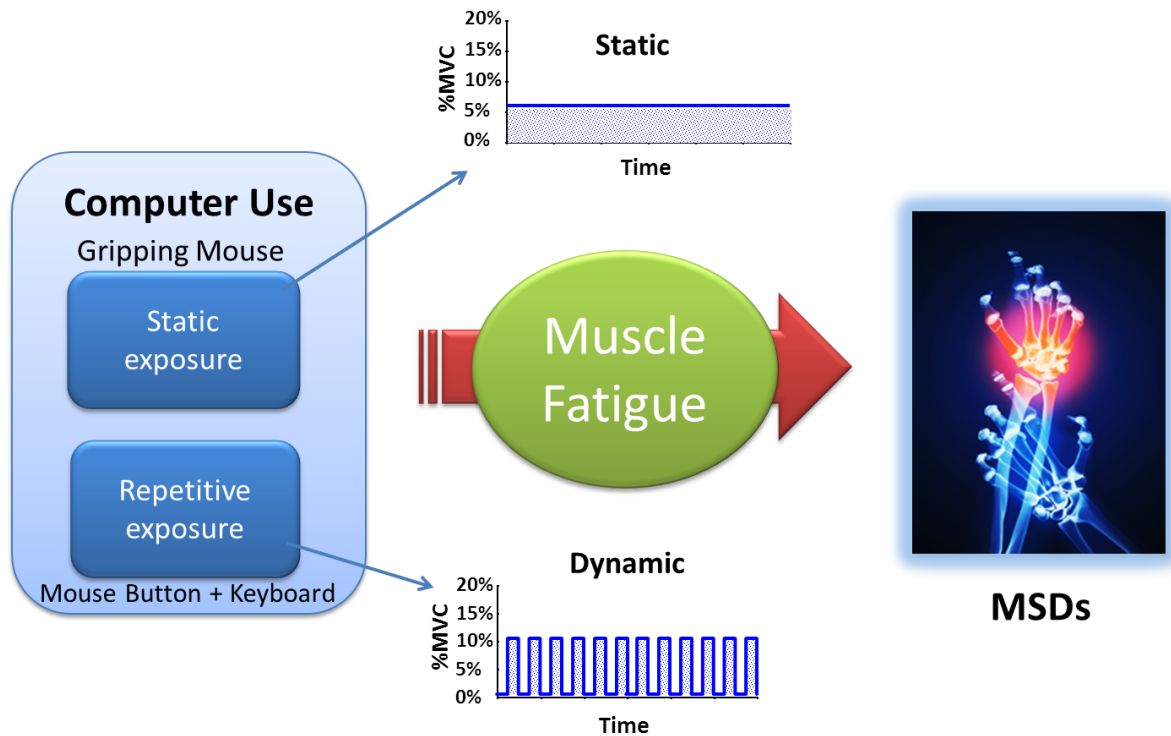


Figure 1.3 Computer use and MSDs.

Mouse use requires static muscle activity which is strongly related to upper extremity discomfort and MSDs (Chang et al., 2007; S. Ijmker et al., 2007; Jensen, Finsen, Sogaard, & Christensen, 2002). Since static postures and muscle loading tend to cause more problems than the dynamic counterparts, mouse use is thought to have stronger relationship with MSDs than keyboard use. Indeed, as shown in Figure 1.4, many epidemiological studies have demonstrated that the risk estimates for hand-arm MSDs are consistently greater with mouse use when compared to those associated with keyboard use (S. Ijmker et al., 2007). In terms of usage time, mouse use durations are typically four-fold greater than keyboard use duration

on average (Chang et al., 2007; Mikkelsen et al., 2007). The static postures and longer duration of mouse use might account for the stronger association with MSDs.

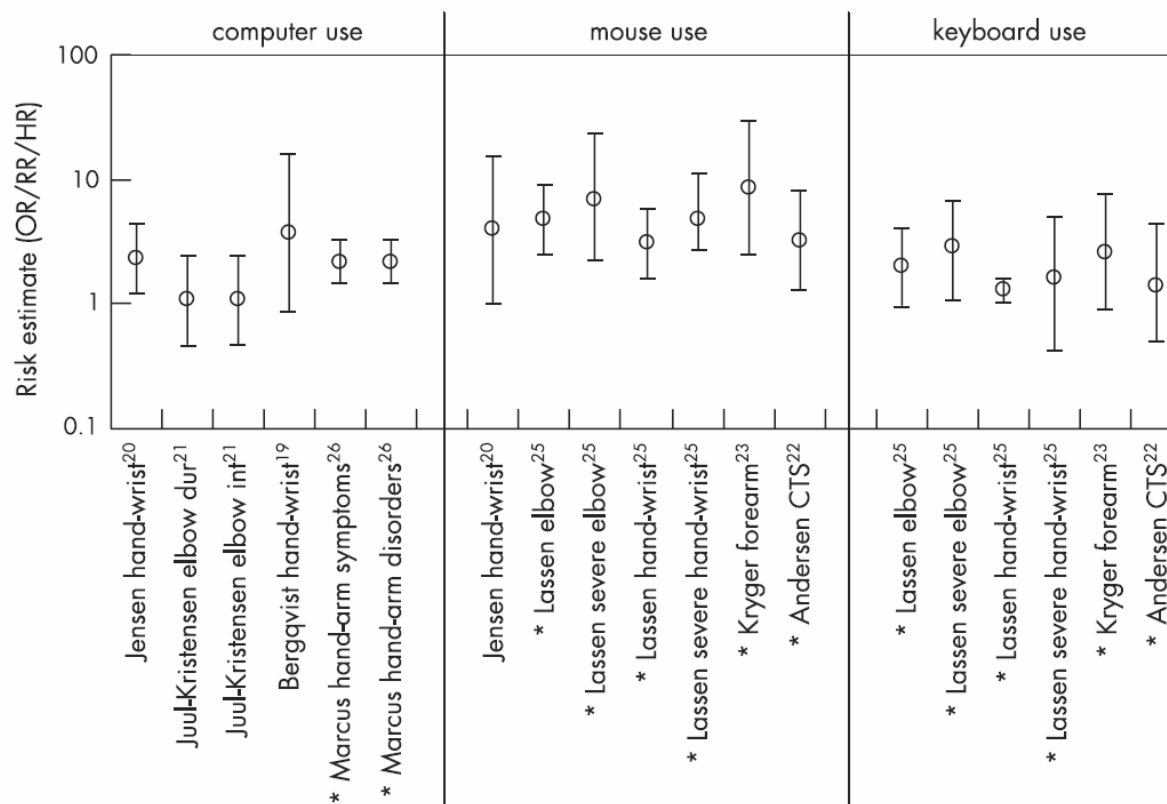


Figure 1.4 Risk estimate between computer use and MSDs. (Ijmker et al., 2007)

1.1.2 Populations at risk

Numerous studies have documented gender-related differences in muscle strength (Miller, Macdougall, Tarnopolsky, & Sale, 1993) and muscle fatigue mechanisms (Hunter, Critchlow, Shin, & Enoka, 2004; Hunter & Enoka, 2001). Miller and his colleagues (1993) have shown that women are approximately 52% as strong as men in the upper extremity but have more fatigue resistance when the same relative work was given. Three major contributors to these gender-based differences in muscle fatigue have been proposed: muscle mass, substrate utilization, and muscle morphology (Hicks, Kent-Braun, & Ditor, 2001).

Due to the inherent gender-related differences in muscle characteristics and fatigue mechanisms, fatigue caused by prolonged, repetitive movements during computer use might also be different in accordance with gender. Despite the large differences between genders in muscle strength, almost all input devices (keyboards and mice) have the same fixed geometrical size and activation force. This one size fits all design paradigm, particularly with respect to keyboard and mouse activation forces, implies that females need to exert almost two-fold more relative force (for as a percentage of the maximum voluntary contraction) than males. The different relative force may explain previous findings that MSDs are known to be more prevalent in female than male population (Wahlstrom, 2005). This might imply that the risk of MSDs during computer use could be different depending upon the gender. Therefore, it might be important to take the gender differences into account when we study the association between computer use and MSDs.

1.2. Muscle fatigue

Although mechanisms underlying computer-work-related MSDs are not fully understood, they are thought to be the result of fatigue and irritation of soft tissues (T. J. Armstrong, Foulke, Martin, Gerson, & Rempel, 1994). Prolonged and repetitive movements during computer input device use can contribute to fatigue in the forearm muscles. Muscle fatigue might be considered as a precursor to MSDs (Peter Wallace Johnson, 1998; D. M. Rempel, Harrison, & Barnhart, 1992). Therefore, it is important to understand the definition and mechanisms of muscle fatigue.

Muscle fatigue is defined as failure to maintain the required or expected force output of the muscle (R. H. Edwards, 1981). Although this classical fatigue definition is widely accepted in various textbooks and in the literature, it does not encompass changes that may

occur during limb movement or the changes in subjective perceptions which can accompany fatiguing contractions (McComas, Miller, & Gandevia, 1995). The more comprehensive definition would be an acute impairment of performance that include both an increase in the perceived effort necessary to exert a desired force and an eventual inability to produce this force (Enoka & Stuart, 1992).

Muscle fatigue can originate from changes that occur anywhere in the motor command pathway (Figure 1.5): motor cortex activation; descending drive; motor neuron excitability and conduction; neuromuscular junction (NMJ) and membrane propagation; excitation-contraction (E-C) coupling; the metabolite pathway; intracellular chemistry; actin-myosin interactions; and blood flow (MacIntosh, Gardiner, & McComas, 2006). As shown in Figure 1.5, changes occurring after NMJ are considered peripheral fatigue while the effects before the NMJ are regarded as central fatigue (Enoka & Stuart, 1992).

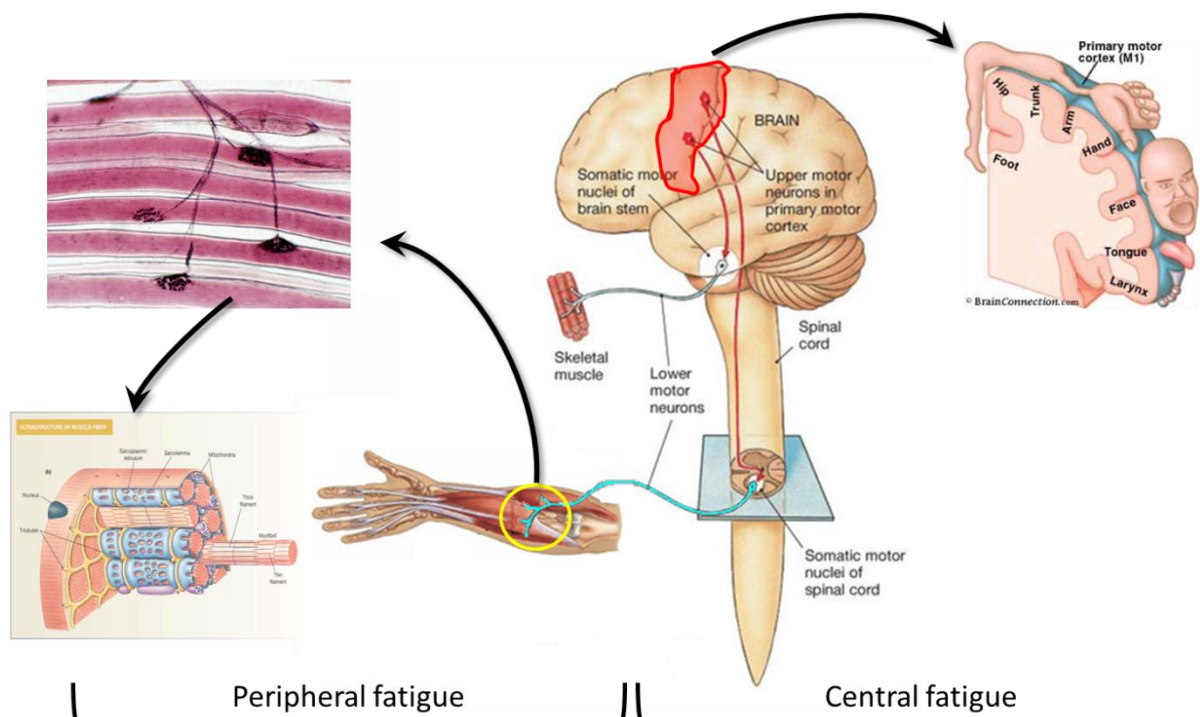


Figure 1.5 The two types and sources of muscle fatigue.

1.2.1 Central fatigue

Since monotonous repetitive typing and/or static mouse operation during computer use could induce boredom, i.e. central fatigue, it is worthwhile to review central fatigue and possible central fatigue mechanisms. Central fatigue can be defined as a progressive reduction of descending central commands from brain during exercise (Roger M. Enoka, 2002; Gandevia, 2001). Muscle fatigue is thought to be affected by this central command as well as by peripheral fatigue mechanisms. Therefore, it is important to understand how central fatigue develops and how the central components have an influence on muscle responses. Including central factors can allow us to create a more comprehensive map of the occurrence of muscle fatigue during computer use.

1.2.1.1 Mechanisms of central fatigue

Despite the importance of central components contributing to muscle fatigue, the establishment of the role of central fatigue in overall muscle fatigue has received relatively little attention (Gandevia, 2001); therefore, the mechanisms of central fatigue are not as well understood compared to the mechanisms of peripheral fatigue (Davis, 1995). Nevertheless, a few previous investigations have revealed that central fatigue might be due to decreased psychological motivation, decreased input to motor cortex, and reduced output from motor cortex or cerebellum (Roger M. Enoka, 2002). Inhibitory or protective reflexes are known to be a possible cause of the changes in motor cortex or cerebellum (Roger M. Enoka, 2002).

1.2.1.2 Measurement of central fatigue

Central fatigue can be measured by either subjective or objective assessment tools. Questionnaires are most commonly used to measure central fatigue because they are easy to implement and inexpensive. A simple objective method for measuring central fatigue is to

use electrical stimulation that delivers a maximal electrical stimulus to either motor nerve or the contracting muscle (Belanger & McComas, 1981). During a maximal voluntary contraction, maximal electrical stimulation is applied to the contracting muscle; then, additional supplemental electrical stimulation is applied. If any additional forces evoked by the supplemental electrical stimulation are observed, then central fatigue is considered to be present since the force output of the muscle wasn't fully realized by the voluntary/central command from the brain. The additional force from the supplemental electrical stimulation is expected to be small without central fatigue but substantial when central fatigue is present. An alternative method using electrical stimulation is to compare the voluntary contraction force to involuntary contraction force of the same muscle (Enoka & Stuart, 1992). However, supramaximal stimulation may not be desirable to measure central fatigue due to substantial pain caused by the stimulation and anatomical variations between subjects (Enoka & Stuart, 1992). Transcranial magnetic stimulation (TMS) has been used to evaluate central fatigue in some previous studies (Liepert, Kotterba, Tegenthoff, & Malin, 1996; Ljubisavljevic et al., 1996; Mill & Thomson, 1995). TMS is a non-invasive and painless method to measure central fatigue by stimulating the human motor cortex (Barker & Jalinous, 1985; Liepert et al., 1996). TMS excites motor cortex trans-synaptically, providing increased muscle responses in cases of central fatigue (MacIntosh et al., 2006). The body of evidence indicates that central fatigue is unlikely to be a factor and occur during computer use due to the very low force requirements.

1.2.2 Peripheral fatigue

Although central fatigue can contribute to muscle fatigue at moderate to high force work (Gandevia, 2001), peripheral fatigue plays a substantial role in the onset and

development of muscle fatigue, especially during moderate to low force work (Biglandritchie, Furbush, & Woods, 1986; Hakan Westerblad, Joseph D. Bruton, David G. Allen, & Jan Lannergren, 2000). Peripheral fatigue is due to any changes occurring at NMJ, E-C coupling processes, metabolites and metabolic pathways, and blood flow (Roger M. Enoka, 2002; MacIntosh et al., 2006); however, peripheral muscle fatigue developed during low intensity work such as computer use is predominantly due to impairment of the E-C coupling process (MacIntosh et al., 2006). A brief review on each of the peripheral fatigue mechanisms is provided below.

1.2.2.1 Mechanisms of peripheral fatigue

Neuromuscular junction

Previous studies have shown that neuromuscular junction (NMJ) failure is primarily the result of severe or extreme muscle fatigue (R. G. Edwards & Lippold, 1956; Lindsley, 1935; Stephens & Taylor, 1972). As shown in Figure 1.6(a) parts 1 and 2, NMJ failure may be caused when axons fail to conduct action potentials (AP) from the motor nerve to the excitable membrane/sarcolemma which covers muscles (Roger M. Enoka, 2002). Highly repetitive activation of motor nerves where numerous APs are transmitted to muscles can deplete neurotransmitters such as acetylcholine (ACh) and therefore result in AP conduction failure and NMJ failure (MacIntosh et al., 2006). The depletion of ACh may be due to a decrease in vesicle release of ACh which occurs in response to repeated APs or the decreased sensitivity of ACh receptors (Roger M. Enoka, 2002). Due to NMJ failure, APs cannot initiate a full muscle contraction. Given the low force requirement, it is highly unlikely that NMJ failure plays a significant role in the development of muscle fatigue during computer

work since the NMJ failure almost always occurs in the presence of very high levels of muscle activity and recruitment.

Excitation-Contraction coupling

Since the impairment of Excitation-Contraction (E-C) coupling has been found to be an important component of muscle fatigue (R. H. T. Edwards, Hill, Jones, & Merton, 1977), E-C coupling failure has been extensively studied as a major factor contributing to peripheral muscle fatigue (Jones, 1996). E-C coupling is a physiological process where an electrical stimulus is converted to a mechanical response (Sandow, 1952). The E-C coupling process starts as an AP is propagated into a muscle fiber through T-tubules (Figure 1.6(a)). The AP in the tubules activates voltage sensitive dihydropyridine (DHP) receptors which trigger ryanodine receptors (RYRs) opening (Figure 1.3 (b), parts 3 and 4). Intracellular Calcium ions (Ca^{2+}) are released from sarcoplasmic reticulum (SR) into cytoplasm (Figure 1.6(b), part 4). The released Ca^{2+} binds to troponin on the actin filaments (Figure 1.6(b), parts 5 and 6), allowing movement of muscle fibers via strong actin-myosin binding (Figure 1.6(b), part 7). Then, the Ca^{2+} is continuously taken back into SR by ATP-driven Ca^{2+} pump (MacIntosh et al., 2006; H. Westerblad, J. D. Bruton, D. G. Allen, & J. Lannergren, 2000).

In the E-C coupling process, there are several places along the chain of events which can lead to muscle fatigue. Depending on where the failure occurs in the process, muscle fatigue could further be characterized as either high or low frequency fatigue (Biglandritchie, Jones, Hosking, & Edwards, 1978). High frequency fatigue (HFF) is where the muscle does not maintain force output when stimulated at high frequencies whereas low frequency fatigue (LFF) is characterized by the relatively greater loss of the muscle's force in response to low

frequency stimulation when compared to the force loss at high frequencies of stimulation (Jones, 1996; Keeton & Binder-Macleod, 2006).

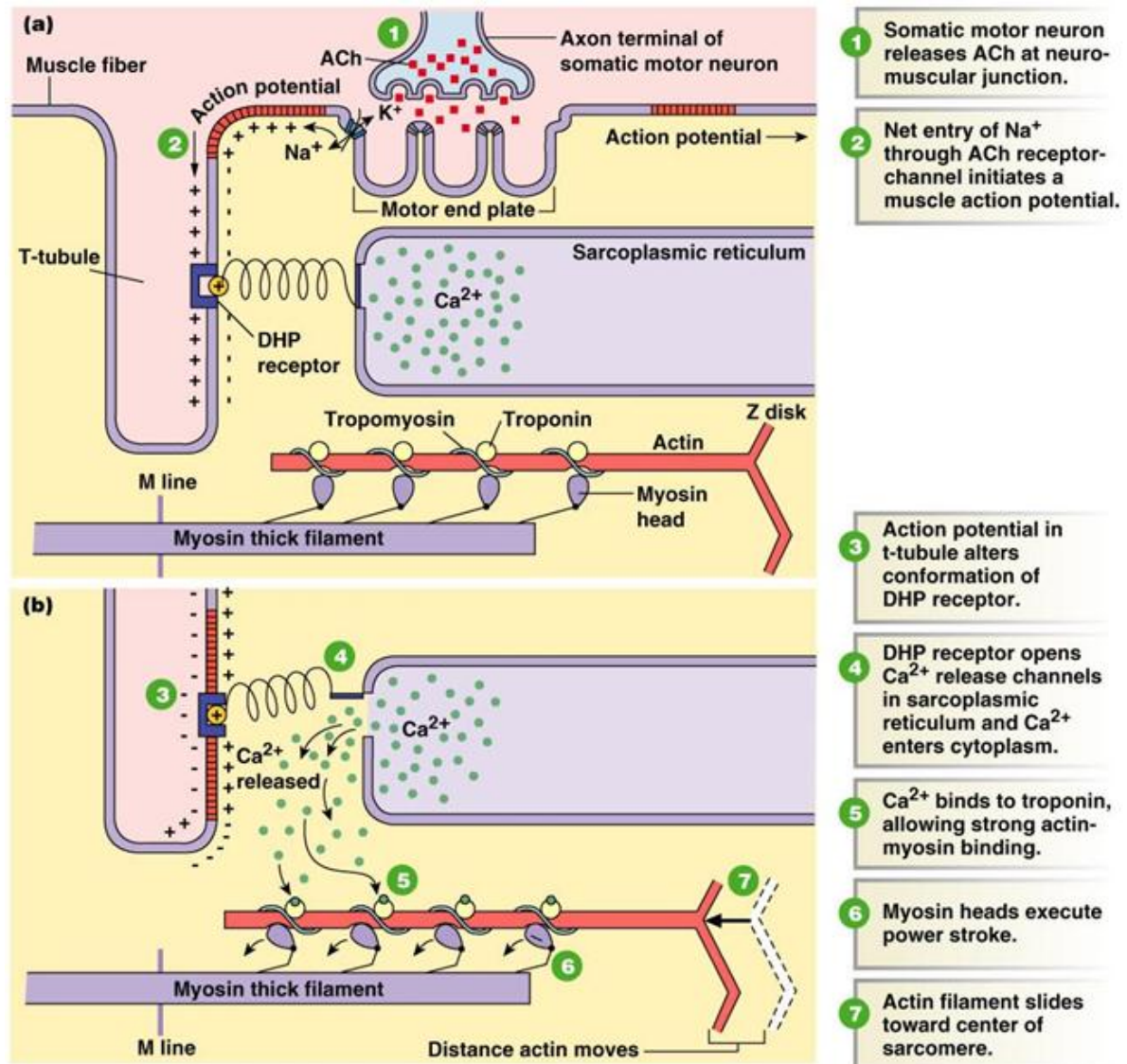


Figure 1.6 Excitation - Contraction coupling (Silverthorn, 2007)

Failure of propagating APs into T-tubules (Figure 1.6(b), part 2 and 3) can be a possible cause of HFF (Cairns, Taberner, & Loiselle, 2009; Edman & Lou, 1992; MacIntosh et al., 2006). A reduction in the number of Potassium ion (K^+) pumps working in the T-

tubules can result in higher K^+ concentration which reduces the T-tubule's membrane potential and eventually slowing or blocking AP propagation into the center of muscle (Fambrough, Wolitzky, Tamkun, & Takeyasu, 1987; Hodgkin & Horowicz, 1959). The failure of AP propagation due to high concentration of K^+ has been known to be a major cause of HFF (Biglandritchie et al., 1978; Jones, 1996).

Another possible cause of the impairment of E-C coupling is the decrease in either Ca^{2+} concentration (Allen, Lee, & Westerblad, 1989; Fitts & Balog, 1996; J. A. Lee, Westerblad, & Allen, 1991; H. Westerblad et al., 2000) or Ca^{2+} sensitivity (Cooke, Franks, Luciani, & Pate, 1988; Cooke & Pate, 1985; J. A. Lee et al., 1991). As shown in Figure 1.2 (b), parts 5 and 6, Ca^{2+} is critical in muscle contraction since its binding with troponin initiates muscle contraction by allowing myosin heads to bind with actin filaments (H. Westerblad et al., 2000). Reduced Ca^{2+} concentration in cytoplasm has been found during muscle fatigue (Allen et al., 1989; Fitts & Balog, 1996; J. A. Lee et al., 1991); the lower concentration could be due to the reduced Ca^{2+} release from SR (MacIntosh et al., 2006; H. Westerblad et al., 2000). The lower Ca^{2+} concentration implies that there are fewer calcium ions available to bind to troponin and therefore, muscle contraction fails. The reduced Ca^{2+} release from SR has been thought to be a possible mechanism of LFF (Chin, Balnave, & Allen, 1997; Jones, 1996; H. Westerblad et al., 2000).

The decreased Ca^{2+} sensitivity could also result in the failure of E-C coupling (Cooke et al., 1988; Cooke & Pate, 1985; J. A. Lee et al., 1991). The lower sensitivity may reduce the interactions between Ca^{2+} and troponin; consequently, the number of the binding sites between myosin heads and actin decreases. This reduced number of the binding sites may be attributed to the reduced contraction force in the presence of muscle fatigue (Lieber, 2002).

It is thought that changes in the E-C Coupling may be a substantial contributor to any changes in muscle fatigue measured with computer use.

Biochemical changes in muscle fibers (metabolites and ATP)

Changes in the biochemical composition of muscle fibers have also been shown during muscle fatigue (MacIntosh et al., 2006). Accumulation of Hydrogen ions (H^+) has been identified in fatigued muscles. High concentration of H^+ could lower intra- (or extra-) cellular muscle pH which is known to reduce muscle contraction force (Donaldson & Hermansen, 1978) and the maximum speed of muscle shortening (Edman & Mattiazzi, 1981). The concentration of both inorganic phosphate and diprotonated inorganic phosphate also increases in muscle fatigue (MacIntosh et al., 2006). High concentrations of inorganic phosphate (Cooke & Pate, 1985) and diprotonated inorganic phosphate (Nosek, Fender, & Godt, 1987) are thought to be associated with the decreased force output from the muscle during muscle fatigue. Since ATP binding to myosin heads allows myosin to dissociate from actin, APT depletion lengthens the duration of the muscle contraction by delaying the muscle's ability to relax. The loss of ATP is known to result in high concentration of Ca^{2+} because Ca^{2+} pumps at SR are ATP-driven. The high concentration of Ca^{2+} also lengthens the duration of the muscle contraction by delaying the muscle's ability to relax (Caputo, Edman, Lou, & Sun, 1994). This prolonged relaxation is one of the typical characteristics of muscle fatigue. Since changes in intra- (or extra-) cellular muscle pH, inorganic phosphate and deprotonated inorganic phosphate usually occur at higher force levels and recovery fairly rapidly after the exposure/exercised has ended, these biochemical changes are not likely to play a role in computer-related muscle fatigue.

1.2.2.2 Measurement of peripheral fatigue

Various objective laboratory-based assessment tools have been used to quantify peripheral fatigue (Figure 1.7): surface electromyography (EMG), electrical stimulation, mechanomyography (MMG) and sonomyography (SMG). EMG, MMG, and SMG provide indirect surrogate measures of muscle fatigue at a macro level; however, these measures are known to be insensitive to muscle fatigue developed in low intensity work (Gerard, Armstrong, Foulke, & Martin, 1996). Alternatively, electrical stimulation methods provide direct measures of muscle fatigue measured in a micro level. More importantly, electrical stimulation methods are known to be sensitive to muscle fatigue developed in low intensity work such as computer use (Peter Wallace Johnson, 1998; Mellor & Stokes, 1992). Among those methods, EMG and electrical stimulation have been most commonly used to evaluate muscle fatigue. Therefore, EMG and electrical stimulation will be discussed in detail and other assessment tools will only be briefly described.

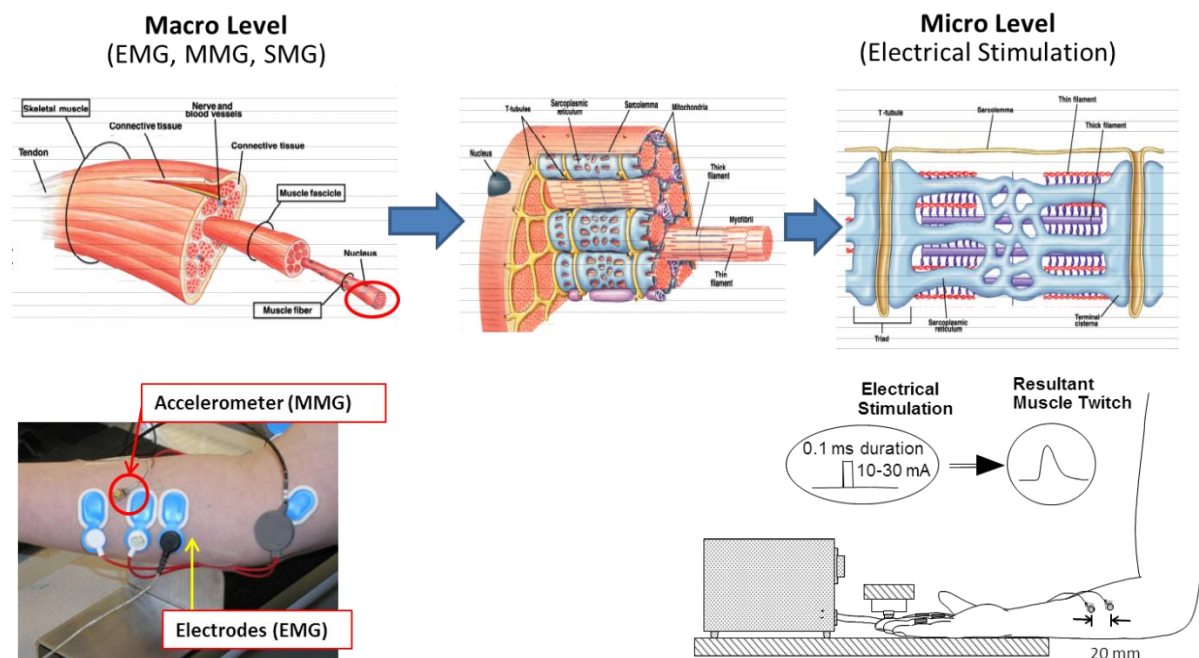


Figure 1.7 Measurement of muscle fatigue at macro and micro levels.

Electromyography (EMG)

EMG is a technique to measure the electrical activity of skeletal muscles. Increased root mean square (RMS) amplitude of an EMG signal or frequency shifts in an EMG power spectrum have been considered an indirect indication of muscle fatigue (Basmajian & De Luca, 1985; Chaffin, 1973; Devries, 1968). Although EMG has been extensively used to evaluate muscle fatigue for several decades, previous investigations (Christensen, 1986; Gerard et al., 1996; Gerard, Armstrong, Franzblau, Martin, & Rempel, 1999; Radwin & Ruffalo, 1999) have found that EMG might not be sensitive enough to measure muscle fatigue resulting from low force and highly repetitive work. Gerard et al. (1996) utilized EMG to measure muscle fatigue during keyboard use; however, they failed to get a consistent indication of muscle fatigue. Because low force and repetitiveness are the major characteristics of computer work, EMG may not be a reliable assessment tool to evaluate muscle fatigue during the computer use.

Electrical stimulation

Electrical stimulation has been considered another objective method to quantify muscle fatigue. Muscle fatigue is measured by either the ratio of contraction forces obtained from low (1 -20 Hz) and high (50 – 100 Hz) frequency stimulation (Byström & Kilbom, 1991; R. H. T. Edwards et al., 1977; Mellor & Stokes, 1992) or by measuring changes in the force output of the muscle in response to only low frequency stimulation (Adamo, Khodaei, Barringer, Johnson, & Martin, 2009; Adamo, Martin, & Johnson, 2002; Bennie, Ciriello, Johnson, & Dennerlein, 2002; Chang et al., 2009; Peter Wallace Johnson, 1998; Peter W Johnson & Crenshaw, 2009). Previous studies have demonstrated that electrical stimulation of the muscle is a suitable and objective method for measuring muscle fatigue (Byström &

Kilbom, 1991; Garner, Hicks, & McComas, 1989; V. Martin, Millet, Martin, Deley, & Lattier, 2004; Mellor & Stokes, 1992).

Despite the effectiveness of electrical stimulation, the traditional approach to measure muscle fatigue using low and high frequency stimulation was found to be problematic due to muscle pain and fatigue caused by the higher frequency stimulation (Peter Wallace Johnson, 1998). Johnson (1998) demonstrated that his method using muscle twitch responses (contraction force, contraction time and one-half relaxation time) evoked by low frequency (2 Hz) stimulation was effective in measuring muscle fatigue in finger flexors. By monitoring temporal changes in muscle twitch duration and twitch force, Johnson (1998) showed that physiological status of the muscle can be objectively measured.

Repeated activation of a muscle initially results in muscle potentiation (fatigue stage 1 in Figure 1.8(a)) characterized by increase in twitch force and decrease in contraction and half-relaxation time (Garner et al., 1989; Gossen & Sale, 2000; Green & Jones, 1989; Hamada, Sale, & Macdougall, 2000; Miyamoto, Yanai, & Kawakami, 2011; O'Leary, Hope, & Sale, 1997; Vandervoort, Quinlan, & McComas, 1983). These studies showed that potentiation-mediated mechanisms delay the development of muscle fatigue. Because of the protective effects of potentiation combatting the onset and development of muscle fatigue, if the duration of the exercise is short and/or its intensity is low, the muscle will end up in a state of potentiation (increased force output and a shortened contraction duration) rather than a state of classical muscle fatigue (decreased force output and a lengthened contraction duration). If the exercise lasts long enough or requires a moderate to high force work, potentiation and fatigue can coexist (Fowles & Green, 2003; Grange & Houston, 1991; Rassier & Macintosh, 2000; Vandervoort et al., 1983). With a combined state of potentiation

and fatigue (fatigue stage 2 in Figure 1.8(a)), the muscle twitch force is still elevated (potentiated) but lower compared to when the muscle was in a pure state of potentiation, and muscle twitch duration may start to lengthen (a sign of the onset of muscle fatigue). Previous studies (Peter Wallace Johnson, 1998; Mellor & Stokes, 1992) have shown that lower frequency electrical stimulation methods were more sensitive to detect the aforementioned physiological changes of muscle status, which could develop during low intensity activities such as computer work. Therefore, the low frequency electrical stimulation method was used in this study due to the sensitivity needed to measure muscle fatigue resulting from very low force computer activities.

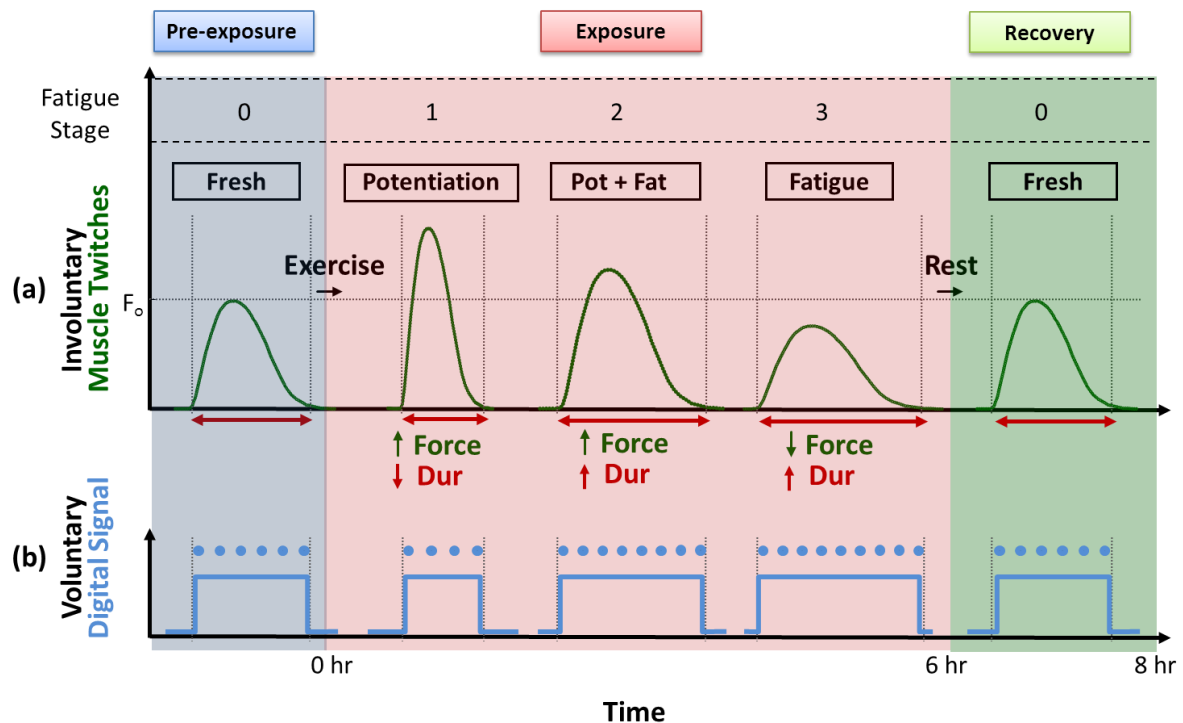


Figure 1.8 Schematic representation of muscle fatigue (a): fresh (0), potentiated (1), potentiated and fatigued (3) and fatigued (4) muscle twitch. The corresponding digital signals measured from the mouse button or keyboard presented to visualize the hypothesis

Other assessment tools

In addition to EMG and electrical stimulation, other assessment tools have also been used to evaluate muscle fatigue. Mechanomyography (MMG) is a method to investigate the mechanical activity of muscles. Similar to EMG, but using an accelerometer mounted over the muscle, changes in in either amplitude and/or frequency of MMG signal can be used indicate muscle fatigue (Esposito, Orizio, & Veicsteinas, 1998). Recently, sonomyography (SMG) has been proposed as a method to assess muscle fatigue (Shi, Zheng, Chen, & Huang, 2007). SMG uses ultrasound images to detect dimensional changes of muscles. In addition, subjective measure of muscle fatigue such as Borg's CR-10 scale has also been widely used to assess perceived fatigue and cannot be ignored because inhibitory feedback such as discomfort, which is a component of perceived fatigue, may proceed the actual physiological measurement of muscle fatigue (Valencia, 1986).

1.3. Research objectives and overview

The objective of this dissertation was to evaluate the onset and development of muscle fatigue in an extrinsic finger flexor muscle as a result of intensive computer use. The study will provide physiological evidence to explain associations between muscle fatigue and computer usage. This study will identify whether a computer monitoring program developed in our lab can be used to measure and detect subtle, systematic changes in keystroke and mouse button-click durations. This has not been examined before, but these subtle, systematic changes in keystroke and mouse button-click durations may be related to underlying physiological changes in the muscle and may be indicative of a computer operator developing muscle fatigue. This study is not only very important because of the increasing

number of computer users world-wide but also because intensive computer use can lead to musculoskeletal problems in some computer operators. By measuring temporal changes in the durations of digital signal from mouse button click and keystrokes which may be associated with the onset and development of muscle fatigue, it may be possible to detect early stages of muscle fatigue and proactively notify computer users of their fatigue; thereby reducing their subsequent chances of developing a computer-related musculoskeletal disorder.

Previous studies have shown that keystroke and mouse button-click durations might be used as surrogate measures to indicate muscle fatigue or physical loading (Chang et al., 2009; Komandur, Johnson, & Storch, 2008). Chang et al. (2009) demonstrated that keystroke durations temporally changed in the presence of fatigue (Figure 1.9). However, the fatiguing exercise in Chang's study was much more intense (either 15% or 30% MVC) when compared to the actual load required during computer use (0.4 to 10% MVC); therefore, the findings may be neither realistic nor generalized to actual computer work. Komandur et al. (2008) showed that mouse button-click durations were affected by physical loading; however, they did not determine whether temporal changes in mouse button-click durations could be used to detect physiological changes in the muscle (e.g. muscle fatigue). Therefore, using the muscle twitch evoked by low frequency electrical stimulation, I want to determine whether muscle fatigue develops during actual computer work; and if so, whether the temporal fatigue-related changes in the muscle twitch durations parallel temporal changes in keystroke and mouse button-click durations.

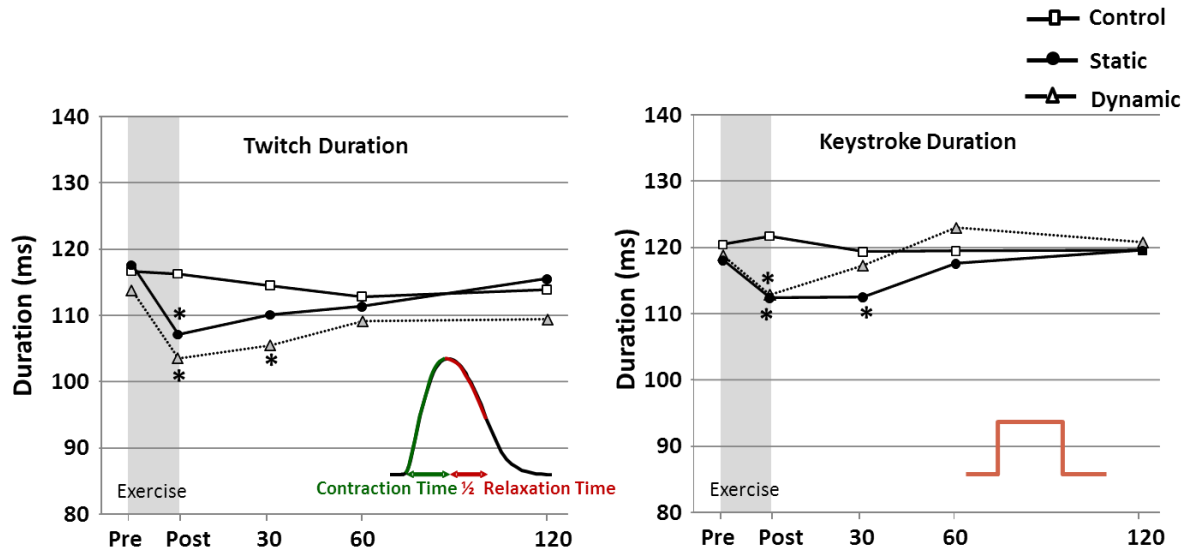


Figure 1.9 Relationships between muscle twitch duration and keystroke durations. Twitch duration is the sum of contraction time and 1/2 relaxation time. The exercise duration was 15 minutes: the static exercise was sustained isometric contraction (constant force) at 15% MVC; the dynamic exercise was fluctuating force exercise (alternating between 200 milliseconds (ms) of 0% MVC and 200 ms of 30% MVC) (Chang et al., 2009)

In order to achieve research objectives, the **first aim** of this dissertation (Chapter 2 and 3) was to verify the reliability, accuracy and sensitivity of my software-based computer input device monitoring program for measuring keystroke and mouse button-click durations. In most previous studies, researchers have used either their own custom-built programs (Chang et al., 2007; Chang et al., 2009; Dennerlein & Johnson, 2006; Komandur et al., 2008) or commercial software (Blangsted, Hansen, & Jensen, 2004; van den Heuvel, de Looze, Hildebrandt, & The, 2003) to collect keystroke and mouse button-click durations. Since these software-based programs are dependent on the computer's Operating System (OS) or have to compete or share the computer's processing power with other software programs, there is a chance that mouse button-click and keystroke duration measurements may not be reliable and accurate. Furthermore, the software-measured keystroke and mouse button-click

durations may depend on the electromechanical and force-displacement characteristic of the switches in the computer input devices. Based on previous studies, changes in the durations of keystrokes and mouse button clicks in the presence of muscle fatigue are expected to be on the order of a few milliseconds; accordingly the measures of keystroke and mouse button-click durations must be accurate and sensitive enough to detect subtle changes down to a few milliseconds. However, the accuracy and sensitivity of keystroke and mouse button-click durations measured by software-based programs has not been verified. Therefore, it is critical to validate the computer monitoring software before investigating whether or not those measures could be accurate, robust, and sensitive enough to measure and detect subtle durational changes indicative of muscle fatigue.

After the measurement system was verified, the **second aim** of this dissertation (Chapter 4) was to determine whether muscle fatigue developed on flexor digitorum superficialis (FDS) during actual computer use (keyboard and mouse use) shown in Figure 1.8(a). The FDS is one of the extrinsic finger flexor muscles on forearm, responsible for flexion and the forces produce by the fingers. An electrical stimulation method developed by Johnson (1998) and used in many studies (Adamo et al., 2009; Adamo et al., 2002; Bennie et al., 2002; Chang et al., 2009) was used to objectively assess muscle fatigue in the present study. Before, during and after computer input device use, the muscle's twitch force responses to electrical stimulation (contraction force, contraction time, one-half relaxation time) were used to identify whether temporal physiological changes in the finger flexor muscle occurred (Figure 1.8(a)). Fatigue stage 3 is classical muscle fatigue characterized by a decrease in muscle twitch force and a lengthening of the muscle twitch duration; however, the classical state of muscle fatigue is usually only observed after moderate to high intensity

work. Since the forces required to operate computer input devices are low (0.4 to 10% MVC), I hypothesize that actual computer use will result in intermediate stages of muscle fatigue (Stage 1 and 2 in Figure 1.8(a)) instead of the classical fatigue; and that these intermediate stages of muscle fatigue can be identified when there are systematic temporal changes in the keystroke and mouse button-click durations (Figure 1.8(b)).

In summary, the study objective was to investigate whether physiological changes in the muscle (i.e. muscle fatigue) can be evaluated using computer activity measures: mouse button-click and keystroke durations. The ultimate goal of the present study was to provide a non-invasive way of identifying physiological changes in the muscles which may be indicative of muscle fatigue, proactively notify the computer operator of these changes, and subsequently reduce a computer operator's chances of developing computer-related MSDs.

Chapter 2 - Validation of computer interaction monitoring program¹

Abstract

Intensive computer use has been associated with musculoskeletal disorders (MSDs). Although the underlying mechanisms are still not fully understood, muscle fatigue is thought to be a contributing factor. Previous studies have shown that keystroke durations are related to muscle twitch durations and may be used as a surrogate measure of muscle fatigue. Software programs have been developed to measure keystroke durations; however, the accuracy of these programs may be influenced by the processing power of the subject's computer and/or the operating system (OS). While 17 subjects performed a series of eight standardized typing tasks over an 8-hour period, keystrokes were collected and analyzed to determine whether there were any differences between keystroke durations measured by an OS-dependent software program residing in the subject's computer and keystroke durations collected directly from the keyboard cable before reaching the computer using a USB analyzer (gold standard). The results demonstrated that the OS-dependent software program underestimated keystroke durations by 3.8 ms (99.6 ± 3.1 vs. 102.9 ± 3.2 ms; $p < 0.0001$); however, based on the results from the 17 subjects and 8 temporal measurements, keystroke durations were highly correlated between the two systems ($r = 0.994$). Despite the small differences, the high individual and temporal correlations between systems indicated that the software program could be used to detect small difference and small temporal changes in keystroke durations.

¹ 61th Annual Industrial Engineering Research Conference, Reno, NV (abstract)

33rd International Conference of the IEEE Engineering in Medicine and Biology Society, Boston, MA (full paper)

2.1. Introduction

Intensive computer use has been known to increase the risk of developing musculoskeletal disorders (MSDs) (Bergqvist, Wolgast, Nilsson, & Voss, 1995; Blatter & Bongers, 2002; Fredric Gerr et al., 2002; Marcus et al., 2002). Physical or biomechanical risk factors for MSDs include force, repetition, posture and the duration and distribution of these exposures (S. Ijmker et al., 2007; D. M. Rempel et al., 1992; Tayyari & Smith, 1997). Previous studies have already shown that the rapid and repetitive finger movements during keyboard use and prolonged static muscle loading during mouse use are associated with upper extremity MSDs (Chang et al., 2007; S. Ijmker et al., 2007; Jensen et al., 2002).

Since most work-related MSDs develop from the accumulation of micro trauma to the soft tissues (muscles, tendons, ligaments and nerves) over time (Punnett & Wegman, 2004), an early detection of physiological changes (i.e. muscle fatigue) may reduce a computer operator's subsequent chances for developing MSDs. In order to detect computer-related muscle fatigue in field settings, it is essential to have a reliable and non-invasive muscle fatigue assessment method. There are lab-based methods to measure muscle fatigue (electrical stimulation of the muscle, electromyography, mechanomyography, etc.); however, these methods may not be suitable in field-based studies due to invasiveness, portability and cost.

Using software that measured the duration of the digital ON/OFF signal, Change et al., (2009) found that keystroke durations changed in the presence of muscle fatigue and paralleled fatigue-related changes measured from muscle twitch durations in the finger flexor muscles. Using similar software, Komandur et al., (2008) demonstrated that mouse button-click durations may also be a surrogate measure for finger flexor muscle twitch durations. .

The accuracy of these software programs for measuring keystroke and/or mouse button click durations have never undergone rigorous validation and may depend on the computer and/or Operating System (OS). Some studies have verified the performance of these OS-dependent software programs (Blangsted et al., 2004; Hwang, Wang, Liang, & Luh, 2009); however, these studies only validated the software's performance for measuring the total number of keystrokes and mouse button clicks and the total duration of computer use (Blangsted et al., 2004; Hwang et al., 2009) but not the individual keystroke or mouse button-click durations .

If temporal changes in keystroke and/or mouse button-click durations can be used as surrogate measure of muscle fatigue, we need to be sure that our software-based monitoring programs have the accuracy and sensitivity to measure and detect small differences or changes in keystroke and mouse button-click durations. Therefore, the present study was conducted to assess the accuracy and sensitivity of a LabVIEW-based software program developed in the Ergonomics Lab at the University of Washington for measuring keystroke durations and detecting small differences and/or changes in keystroke durations while subjects completed a series of eight standardized typing tasks over an 8-hour period.

2.2. Methods

2.2.1 Subjects

Through e-mail solicitations (Appendix A), a total of 17 subjects including 8 males and 9 females were recruited to participate in this experiment. All the participants were touch-typists without a history of upper extremity MSDs. The average typing speed was 59.2 (SD 13.3) words per minute (WPM), ranging from 42 to 85 WPM. The average age of the

participants was 23.8 (SD 4.1) years old, ranging from 20 to 34 years. The experimental protocol was approved by the Human Subject Committee at the University of Washington (IRB#: 38609), and all subjects provided their written informed consent before participating in the experiments.

2.2.2 Experimental design

The experiment was a repeated measures design where the keystroke durations were measured from each subject for 2 minutes over eight time periods which spanned 8-hours. The subjects typed on a standard keyboard (model SK-8115; Dell Inc; Round Rock, TX) and were instructed to type at their own pace mimicking their actual typing habits. The workstation was adjusted based on subject's anthropometric data in accordance with ANSI/HFES 100-2007.

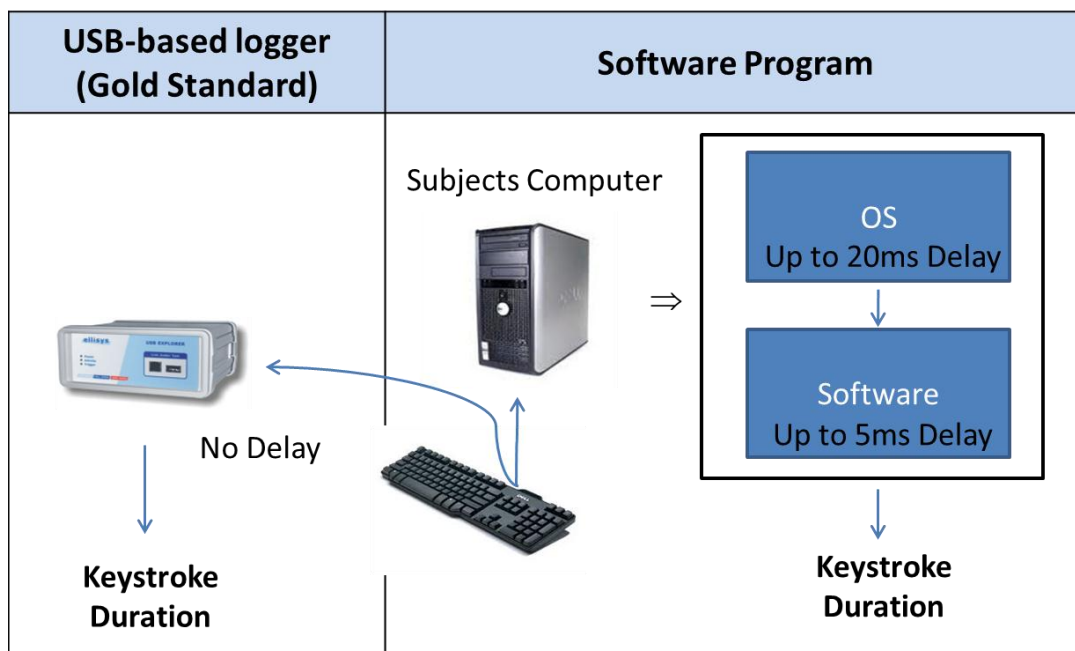


Figure 2.1 The configuration of measurement systems including the external USB logger and software program.

During the typing tasks, keystroke durations were measured by both an external USB logger (USB Explore 200 Professional Edition; Ellisys Inc; Geneva, Switzerland) and a computer monitoring program developed using LabVIEW software (Version 7.1; National Instruments; Austin, TX, USA). The external logger collected keystroke durations directly from the keyboard with the precision of ± 17 nanoseconds and saved the keystroke duration data on a separate host computer (Figure 2.1). In parallel, the LabVIEW-based computer monitoring program, installed in the subject's computer, registered keystrokes with a resolution of approximately ± 5 milliseconds (ms). As shown in Figure 2.1, the major difference between systems was the LabVIEW-based program was subject to program specific delays, plus any potential delays associated with the probabilistic operation of the Windows Operating System, which could be up to 20 ms. In comparison, the external USB logger was not affected by OS, other software programs, or delays since it registered all the digital signals directly from the keyboard's USB cable before the digital signals reached the subject's computer.

2.2.3 Data analysis

Since one of the ultimate goals of this dissertation is to compare the keystroke durations with ballistic/rapid muscle twitch contractions, only ballistic keystrokes from the alphabetic keys were analyzed. Other keys such as space, shift, control, alt, numeric and functional keys were omitted from the analysis since these keys likely have different or non-ballistic key activations.

The statistical analysis was conducted in JMP (Version 8.0.2; SAS Institute Inc.; Cary, NC, USA). A *mixed model with restricted maximum likelihood estimation* (REML) was used to determine whether there were differences in keystroke durations measured by the

external USB logger and the software program. In the model, the device and measurement time were included as fixed effects while subject was included as a random effect.

2.3. Results

The external USB logger collected a total of 27,136 keystrokes from all the participants whereas the software-based program collected 27,035 keystrokes, a difference of 101 keystrokes or 0.37% of the total keystrokes collected. The keystroke durations measured by the software program were significantly shorter than those measured by the external logger (99.6 ± 3.1 vs. 102.9 ± 3.2 ms; $p < 0.0001$) (Figure 2.2(a)). The software-based measures were almost perfectly correlated with the logger-based measures ($r=0.994$). That is, these differences between two measurement tools were consistent at the individual level (Figure 2.2(b)).

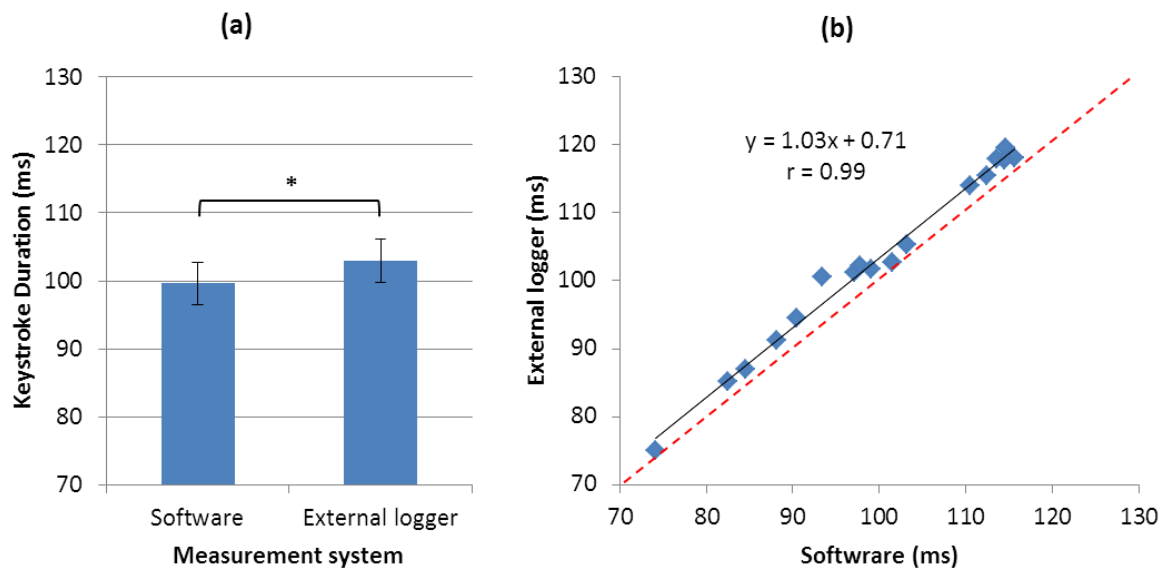


Figure 2.2 Comparison of external-logger-based and software-based keystroke durations: (a) the differences in keystroke durations between the external USB logger and software program; (b) a linear fit and correlation between the two different measures. Asterisk denotes statistical significance ($p < 0.05$). The dotted line is the identity line. [$n = 17$]

The keystroke durations did not differ across the eight measurement times ($p = 0.84$). The interaction between the device and measurement time was not significant ($p = 0.87$), meaning that the keystroke durations measured by the software program were consistently shorter than those measured by the external logger (Figure 2.3).

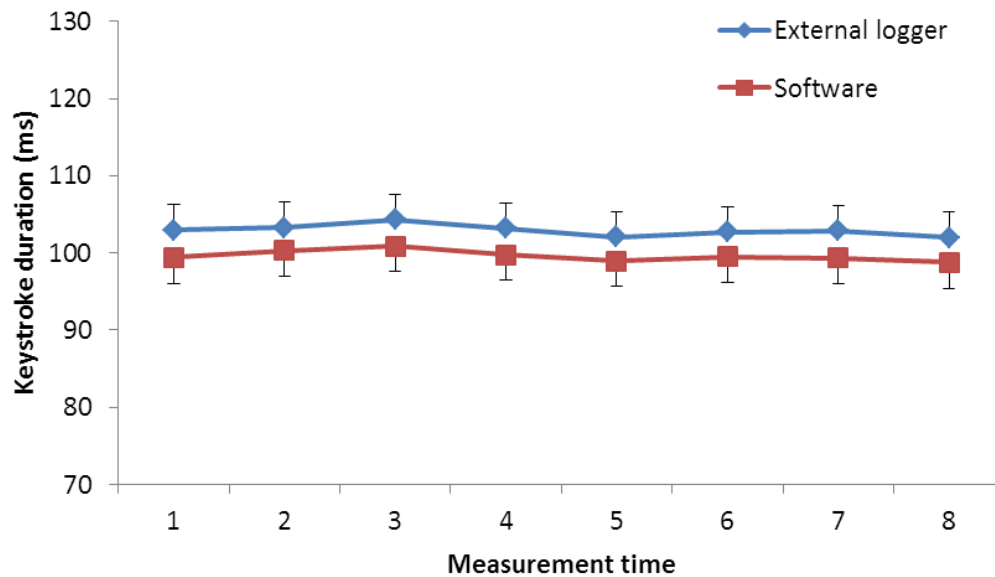


Figure 2.3 The differences in keystroke durations between the external USB logger and software program across the eight measurement times. [n = 17]

2.4. Discussion

Previous studies have shown that small, systematic changes in software-measured keystroke durations may be used to indicate temporal physiological changes in the fatigue status of the muscle (Chang et al., 2009). To measure small subtle changes in keystroke durations, a software program should have both the accuracy and sensitivity needed to detect small changes in keystroke durations. Therefore, the present study evaluated the sensitivity and accuracy of a software program for measuring keystroke durations. In order to use small,

systematic changes in keystroke durations as a surrogate measure of muscle fatigue, the data collection tool must have the requisite sensitivity and accuracy. Therefore, we evaluated the sensitivity and accuracy of a software-based keystroke duration measurement program against an external USB logger which measured keystroke durations directly from the keyboard.

The results indicated that the software program underestimated keystroke durations by approximately 4 ms or 4% on average when compared to the external USB keystroke logger. Furthermore, the software program missed a small fraction (0.37%) of the total number of keystrokes. Although the keystroke durations measured by the two systems were significantly different, the correlation between the software- and logger-based measures was almost perfect for the subject based correlation ($r = 0.994$), with the fitted line (with the slope of 1.03) very closely approximating the identity line (the red dotted line, slope = 1.0). In addition, the small subject-based and temporal differences in keystroke durations, down to a few milliseconds, were identified by the software-based tool. Therefore, the keystroke durations measured by the software program accurately mirrored the keystroke durations measured directly by the external USB logger, with exception of a small, constant bias. As shown by the small subject-based differences, this bias, however, does not affect the ability of the software-based program to detect small differences in keystroke durations.

The keystroke durations did not vary across the eight measurements which spanned the eight-hour measurement period. This result indicated that the study apparently did not cause or induce any fatigue-related changes on keystroke durations. Despite the small, insignificant temporal differences across the eight measurements, the software-based measures paralleled the logger-based measures (Figure 2.3). In other words, the software

program was sensitive enough to detect the small temporal changes captured by the external USB logger.

Although we assumed that the software program may depend on OS and computer processing power, the tests were only conducted on one computer. Therefore, future studies could investigate computers with different processing speeds and different variants of the Windows Operating Systems. Furthermore, since mouse click duration may also be used as a surrogate measure to indicate muscle fatigue, it would be beneficial to evaluate the software program's sensitivity and accuracy for mouse button click durations. However, since the processing the digital signals from the mouse button are identical to the processing of keystrokes, the results for the mouse button-click duration should be very similar if not identical.

In conclusion, our software program appears to have the sensitivity and accuracy for detecting small subject- and time-dependent changes in keystroke durations; therefore, it may be a viable exposure assessment tool for detecting small, systematic temporal changes in keystroke durations. Ultimately, these small, systematic changes in keystroke durations may be used to proactively detect when computer operators may be developing muscle fatigue and reduce a computer operator's subsequent chances of developing a computer-related MSD.

Chapter 3 - Viability of Using Digital Signals from the Keyboard to Capture Typing Force Exposures²

Abstract

Although previous studies have shown that systematic temporal changes in keystroke durations may be used as surrogate measures of muscle fatigue, software-based keystroke duration may be adversely affected by keyboards with different keyswitch force-displacement characteristics. Therefore, the purpose of this study was to use a force platform to measure keystroke durations from the individual keystroke force profile and compare them to software-based keystroke duration measures in order to determine whether the software-based keystroke durations were accurate surrogate measures for the force-derived keystroke durations (gold standard). A total of 13 subjects typed for 15 minutes each on three keyboards with roughly the same activation force (0.6 N) but with three different key travel distances (1.8, 2.0, and 4.0 mm). The results showed that the software-based keystroke durations closely mirrored and approximated the true force-derived keystroke durations, regardless of the keyboard force-displacement characteristics. Furthermore, the subject-dependent correlations indicated that the software-based keystroke durations accurately reflected the small differences in the true force-derived keystroke durations. Since small temporal changes in the force-derived keystroke durations are most closely related to the physiological fatigue-based changes in the force output of the muscle, the fact that software-based keystroke durations closely mirrored the force-derived keystroke durations indicates the software-based keystroke durations are also closely tied to physiological, fatigue-based

² Journal, *Ergonomics* (in press)

Journal, *Work* No. 4 pp. 2588-2590 (published as supplementary in 2012)

changes in the force output of the muscle. Ultimately, we hope these small changes in keystroke durations may be used as a surrogate cost-effective measure to identify muscle fatigue and to proactively notify a computer user when they are developing muscle fatigue; therefore, reducing their subsequent chances of developing a computer-related musculoskeletal disorder.

3.1. Introduction

Although intensive computer use has been associated with musculoskeletal disorders (MSDs) in the upper extremities (Chang et al., 2009; F. Gerr et al., 2006), the association between computer use and MSDs has long been debated. Recently, Ijmker et al (2011) and Gerr and Fethke (2011) revived the debate on this issue. A part of main reasons for this longstanding debate may be due to the lack of clinical diagnosis for MDS despite a high prevalence of self-reported symptoms (Waersted, Hanvold, & Veiersted, 2010). Also, a main reason for this longstanding debate is that the exposure-response relationship between computer use and MSD-related injuries are not fully understood. Developing an adequate, non-invasive, cost-effective, exposure assessment method for large scale epidemiological studies on computer use could contribute to the growing body of knowledge on potential injury underlying mechanisms.

Previous studies have shown that rapid and repetitive finger movements during keyboard use and prolonged static muscle loading during mouse use are associated with upper extremity MSDs (S. Ijmker et al., 2007; D. M. Rempel et al., 1992; Tayyari & Smith, 1997). Most work-related MSDs develop from the accumulation of micro trauma to the soft tissues (muscles, tendons, ligaments and nerves) over time (Punnett & Wegman, 2004) and

muscle fatigue is believed to be a precursor to MSDs (D. M. Rempel et al., 1992). Accordingly, an early detection of the physiological detriment (i.e. muscle fatigue) may reduce a computer operator's subsequent chances for the onset and development of a computer-related MSD. There are several laboratory-based assessment tools to objectively measure muscle fatigue (electrical stimulation, electromyography, and mechanomyography); however, due to their invasiveness, lack of portability and cost, these measurement tools may not be appropriate for measuring computer-related muscle fatigue in field-based or occupational settings.

An exposure-response relationship has been shown between muscle fatigue and its effect on keystroke durations. Chang et al. (2009) showed that keystroke durations measured from individual keystrokes systematically changed in the presence of muscle fatigue. In Chang's study, muscle fatigue was assessed by measuring the muscle's twitch force response (twitch force and twitch duration) to electrical stimulation. Chang found that the temporal changes in the muscle's twitch force response, which was indicative of fatigue, was mirrored by the temporal changes in keystroke durations, and therefore concluded that small, systematic temporal changes in keystroke durations may be an objective surrogate measure of muscle fatigue. Because the small, systematic temporal changes are usually small (2 to 10 milliseconds), a reliable assessment tool to measure small, systematic, temporal changes in keystroke durations has to be accurate and sensitive.

Keystroke durations can either be measured non-invasively using keyboard monitoring software or more invasively using a force platform mounted under the keyboard. Force platforms have been used to objectively assess typing force exposures including force, frequency, and duration of keystrokes (Jindrich, Balakrishnan, & Dennerlein, 2004a, 2004b;

Radwin & Jeng, 1997; Radwin & Ruffalo, 1999; D. Rempel, Dennerlein, Mote, & Armstrong, 1994). Keyboard monitoring programs can provide information on keystroke frequency and duration; however, it is not known whether keyboard force-displacement characteristics affect the measurement of keystroke durations. The software-based keystroke durations may be affected by the electromechanical make- and release-point when the key is pressed and released, whereas keystroke durations measured by force platforms will not be affected by the electromechanical differences in keyswitch designs. The tradeoff between the two methods is cost and methodological complexity. For large-scale epidemiological studies, force platforms may not be appropriate due to their invasiveness and cost. In addition, since small temporal changes in the force-derived keystroke durations are most closely related to physiological fatigue-based changes in the force output of the muscle, if the software-based keystroke durations closely mirror the force-derived keystroke durations, then the software-based keystroke durations will also be a surrogate for the physiological, fatigue-based changes in the force output of the muscle,

Therefore, using keyboards with different force-displacement characteristics, this study used a force platform to measure the keystroke durations directly from individual keystroke force profiles and compared them to software measured keystroke durations. The purpose of the study was to determine whether the software measured keystroke durations derived from the digital signal were related to the force-derived keystroke durations and could be used as a non-invasive, surrogate measure in lieu of the more invasive measurements collected with a force platform.

3.2. Methods

3.2.1 Subjects

Through e-mail solicitations (Appendix B), a total of 13 subjects including 6 males and 7 females were recruited to participate in this study. All participants were right-handed touch typists with no history of upper extremity MSDs. The average age of the participants were 26.9 years old (SD: 7.9), ranging from 20 to 49 years old. Their average years of computer use were 13.4 years (SD: 4.9). The experimental protocol was approved by the Human Subject Committee at the University of Washington (IRB# 37905), and all subjects provided their written informed consent before participating in the experiments.

3.2.2 Experimental design

The experimental task consisted of having subjects type for 15 minutes each on the three keyboards which were mounted on top of a force platform. The workstation was adjusted based on the subject's anthropometry in accordance with ANSI/HFES 100-2007. The chair was adjusted so the subject's feet rested firmly on the floor. With subjects relaxing their shoulders, resting their arms comfortably at their side and forming roughly a 90 degree angle at the elbow, the height of the workstation was adjusted so the table height was set at approximately 2 cm below elbow height. However, subjects were instructed not to rest their hands or wrists on the keyboards or the force platform in order to prevent static resting forces from becoming an additional component of measured typing forces. The monitor was placed at arm's reach with the top of the viewing portion of the screen just below eye level and the keyboard had the spacebar centered on the subject's body.

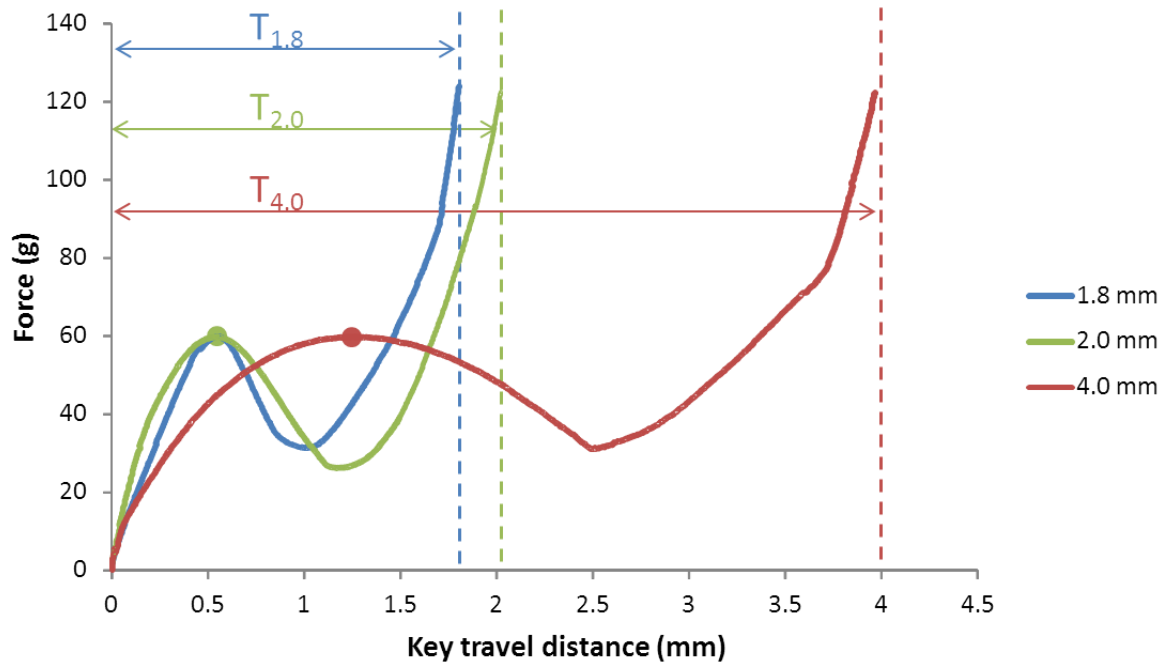


Figure 3.1 Force-displacement curves of three keyboards: 1.8, 2.0, and 4.0 mm. The solid dots indicate the activation forces (make point) and the dashed lines the travel distances. $T_{1.8}$, $T_{2.0}$, and $T_{4.0}$ are the distances between the beginning and the end of key travel for 1.8, 2.0, and 4.0 mm keyboards, respectively.

The three keyboards tested, which had different keyswitch force-displacement characteristics, included: 1) a keyboard with 4.0 mm of key travel (Model SK-8115; Dell Inc; Round Rock, TX), 2) a keyboard with 2.0 mm of key travel (Model HP G62; Hewlett Packard Inc.; Palo Alto, CA) and 3) a keyboard with 1.8 mm of key travel (Model HP Envy; Hewlett Packard Inc.; Palo Alto, CA). Force-displacement characteristics of all three keyboards are shown in Figure 3.1. The keyboard with 4.0 mm travel distance had rubber dome switches whereas the keyboards with 2.0 and 1.8 mm of key travel distance had scissor switches. The activation forces on all the keyboards were approximately 0.6 N. The order of

keyboard use was counterbalanced to minimize any potential confounding due to keyboard testing order.

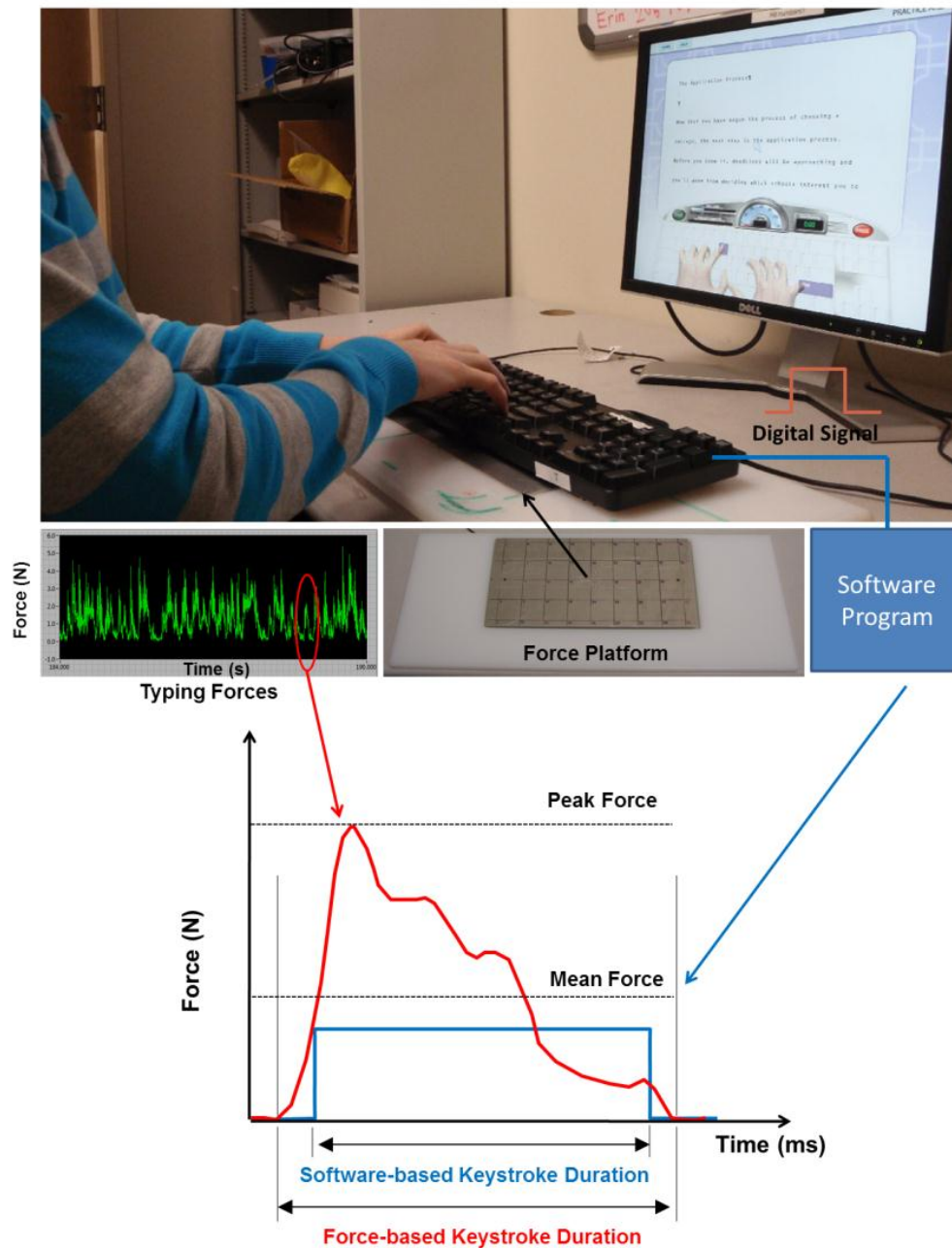


Figure 3.2 Experimental setup and schematic comparisons of the measurement methods: the red and blue solid line represents the force profile and digital signal of an individual keystroke, respectively.

For the typing task, a typing program (Mavis Beacon Teaches Typing - Platinum Edition A; Broderbund Software, Inc.; Novato, CA, USA) was used to evaluate typing performance including typing speed and accuracy. During the typing tasks, keystroke durations were simultaneously collected from the force platform and the keyboard at 500 Hz. The force platform consisted of a 36 cm x 18 cm aluminum plate mounted on top of a force/torque transducer (Mini-40E; ATI Inc.; Apex, NC). Testing over the full area of the force platform demonstrated that the absolute mean force measurement errors over a 0 to 4 N range were less than 10%. The keyboards were placed on the force platform with the “H” key of each keyboard centered over the force transducer. A thin piece of plexiglass surrounded the force platform to offset the height of the platform and create a flat worksurface. The detailed experimental setup is shown in Figure 3.2. Only typing force in the z-direction (downward forces) were analyzed.

3.2.3 Data analysis

The statistical analysis was conducted in JMP (Version 8.0.2; SAS Institute Inc.; Cary, NC, USA). A *mixed model with restricted maximum likelihood estimation* (REML) was used to determine whether there were differences in keystroke durations measured by digital keystroke signals and applied individual keystroke force profiles. In the model, keystroke duration measurement method (digital or force-based), keyboard, hand, and finger were included as fixed effects while subject was included as a random effect. The *Tukey-Kramer method* for multiple comparisons was used to test whether there were differences in keystroke durations between the keyboards. In addition, linear regression methods were used to determine how well the software-based keystroke durations approximated the force-based

measures. All data are presented as mean and standard error; and significance was noted when Type I error was less than 0.05.

3.3. Results

3.3.1 Software-based measures

The software-based keystroke durations from the 1.8, 2.0, and 4.0 mm travel keyboards were 131.7 ($\pm$ 5.48), 122.5 ($\pm$ 5.46), and 94.4 ($\pm$ 5.48) milliseconds (ms), respectively (Figure 3.4(a)). This result indicated that the software-based keystroke durations were dependent on key force-displacement characteristics ($p < 0.0001$). The keystroke durations from the non-dominant left hand were 15.1 ms or approximately 15% longer than those from the dominant right hand on average ($p < 0.0001$) (Figure 3.3 (a)). In addition, the keyboard by hand interactions were not significant ($p = 0.29$); that is, the dominant right hand had shorter keystroke durations than the non-dominant hand regardless of the keyboards. Despite a significant hand by finger interactions ($p < 0.0001$), the keystroke durations from the little and ring fingers were longer than those from index and middle fingers ($p < 0.0001$) as shown in Figure 3.3(b). Lastly, although the keyboard by finger interactions were significant ($p < 0.0001$), all the keyboards showed a similar pattern where the little and ring fingers had longer keystroke durations relative to the index and middle fingers (Figure 3.3(e)).

3.3.2 Force-based measures

The force-based keystroke durations from the 1.8, 2.0, and 4.0 mm travel keyboards were 119.3 ($\pm$ 5.9), 111.3 ($\pm$ 5.9), and 116.2 ($\pm$ 5.9) milliseconds (Figure 3.4(a)), respectively ($p = 0.07$). When compared to the software-based keystroke durations between keyboards, the range of the differences in force-based keystroke durations between keyboards was

smaller. Similar to the software-based keystroke durations, the force-based keystroke durations from the non-dominant left hand were 10.6 ms or approximately 10% longer than those from the dominant right hand ($p = 0.007$) on average (Figure 3.3(c)).

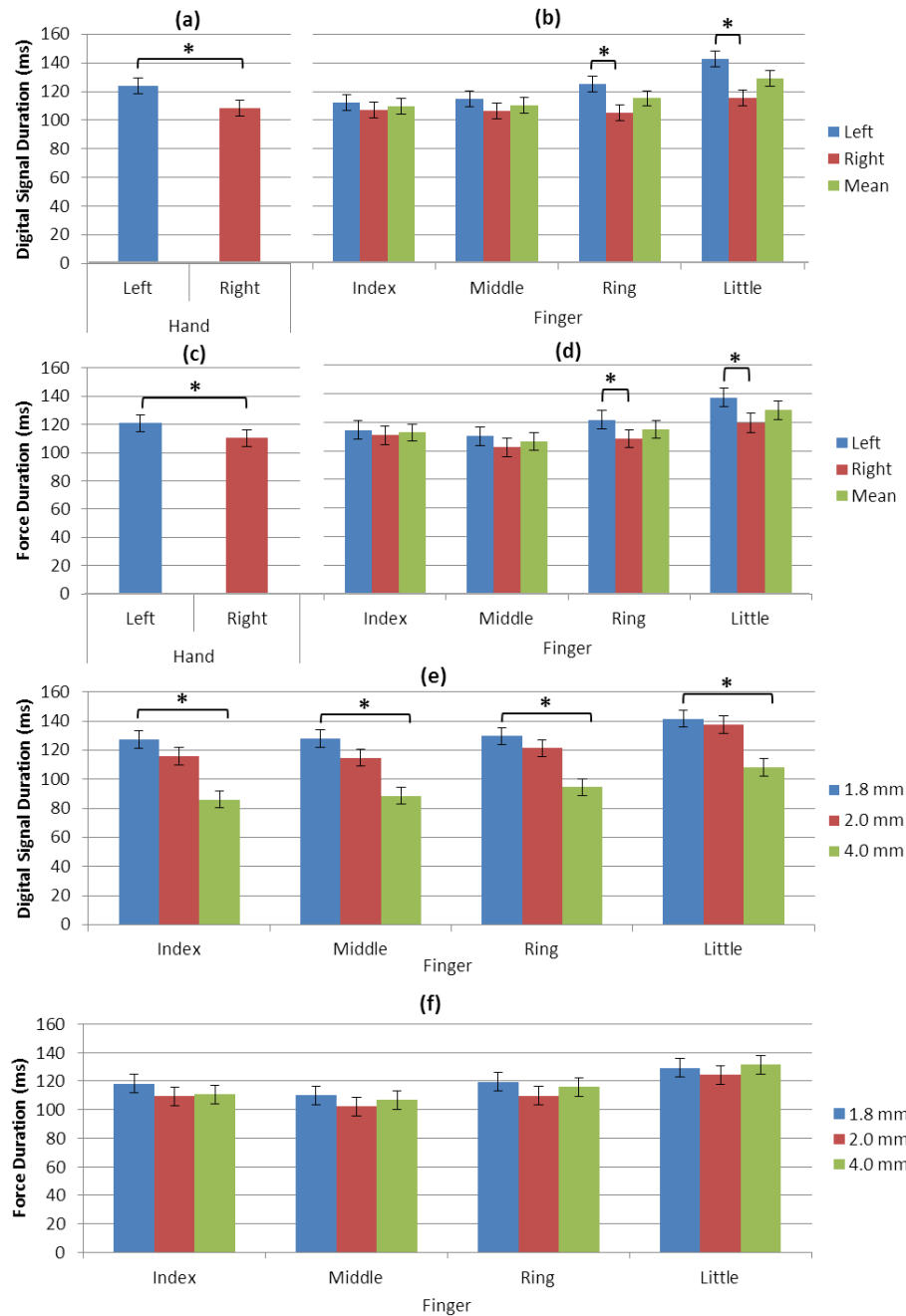


Figure 3.3 Comparisons of software-based keystroke durations [$n = 13$]: (a) by hand; (b) by finger and hand; (e) by finger and keyboard. Comparisons of force-based keystroke durations:

(c) by hand; (d) by finger and hand; (f) by finger and keyboard. Asterisks denote statistical significance ($p < 0.05$).

In addition, there were significant differences in keystroke durations across fingers ($p < 0.0001$); the keystroke durations from the ring and little fingers were longer than those from the index and middle fingers (Figure 3.3(d)). Although the keyboard by hand interactions were significant ($p = 0.014$), the keystroke durations from the right hand were consistently shorter than those from the left hand. The differences between the right and left hand on 1.8 mm keyboard were slightly smaller than those on 2.0 and 4.0 mm keyboards. Despite the significant keyboard by finger interactions ($p=0.0005$), the little and ring fingers had consistently longer keystroke durations across all the keyboards (Figure 3.3(f)). Lastly, the hand by finger interactions were significant ($p < 0.0001$), indicating that finger-related differences in keystroke durations varied depending on hand (Figure 3.3(d)).

3.3.3 Difference between software and force-based measures

The results showed that there were significant differences between the keyboards in the software-measured keystroke durations ($p < 0.0001$) whereas the differences in the force-based measures between keyboards were not as large ($p = 0.07$). The differences between the software- and force-based keystroke durations on 1.8, 2.0, and 4.0 mm travel keyboards were 12.2 ± 1.9 ($p = 0.001$), 10.6 ± 1.9 ($p = 0.001$), and -21.8 ± 1.9 ($p < 0.0001$) milliseconds, respectively. Despite the significant differences, the software-based keystroke durations were highly correlated with the force-based measures (Figure 3.4(b-d)).

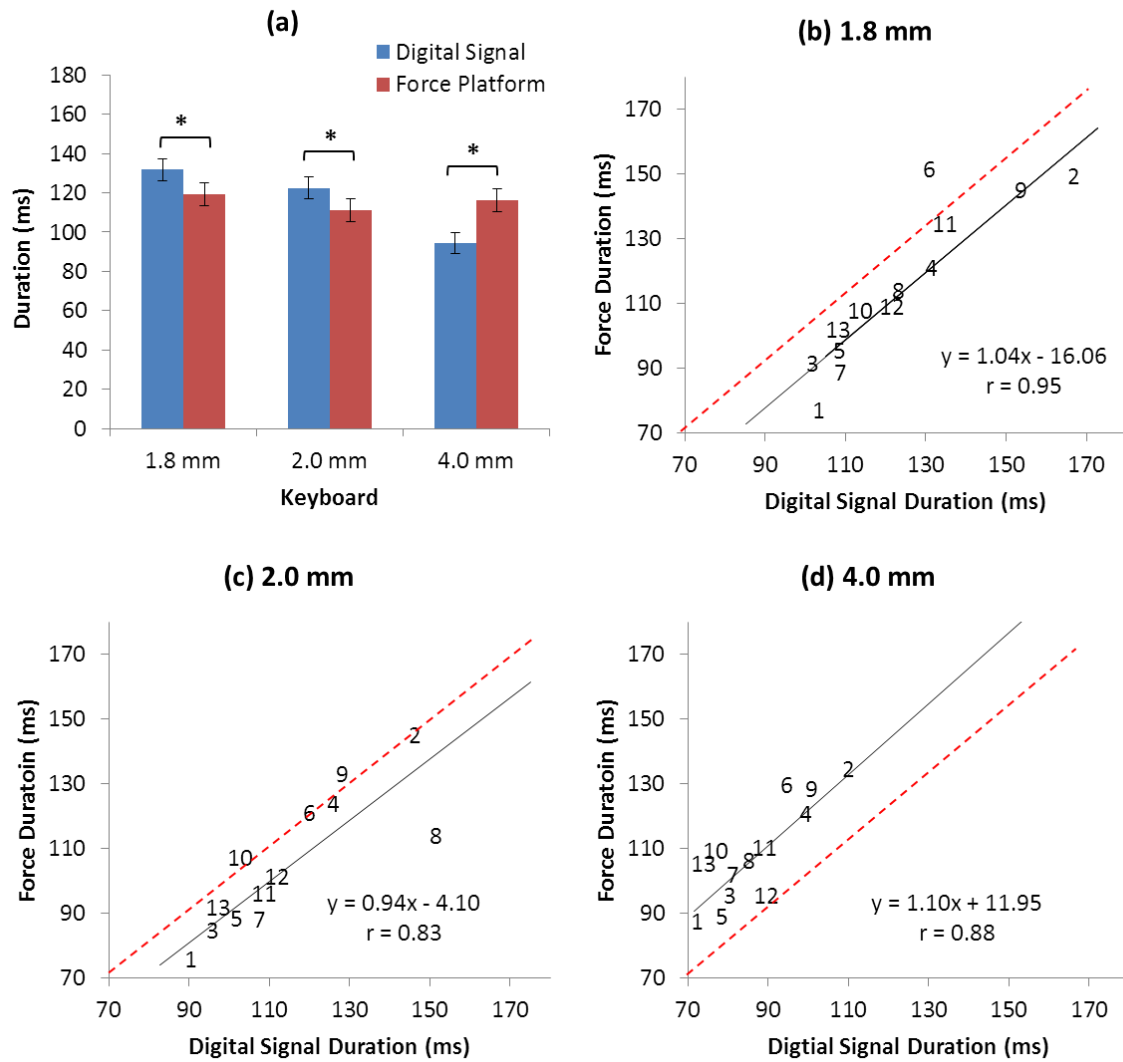


Figure 3.4 Comparisons of software- and force-based keystroke durations [n = 13]: (a) the differences in the two measures grouped by keyboard; (b-c) linear fits and correlations between the keystroke durations measured from digital signals (software) and applied finger forces (force platform) on 1.8, 2.0, and 4.0 mm keyboard, respectively. The numbers on regression plots (b-c) represent subjects. Asterisks denote statistical significance ($p < 0.05$). The dotted red lines are the identity lines.

3.3.4 Typing forces

Typing forces by keyboard, hand, and finger are summarized in Figure 3.5. The results showed that there were keyboard- and finger-related differences in typing forces ($p = 0.0003$ and 0.0001 , respectively) whereas the mean typing forces did not vary by hand ($p =$

0.47) (Figure 3.5(a)). In addition, the two-way interactions between keyboard and hand (Figure 3.5(b)) indicated that differences in keystroke forces between hands were dependent on the keyboard. The significant interactions ($p < 0.0001$) between hand and finger (Figure 3.5(c)) indicated the little fingers had greater differences in keystroke forces when compared to the other fingers with the force differences between the left and right fingers opposite of the other fingers (higher force in the left rather than right little finger).

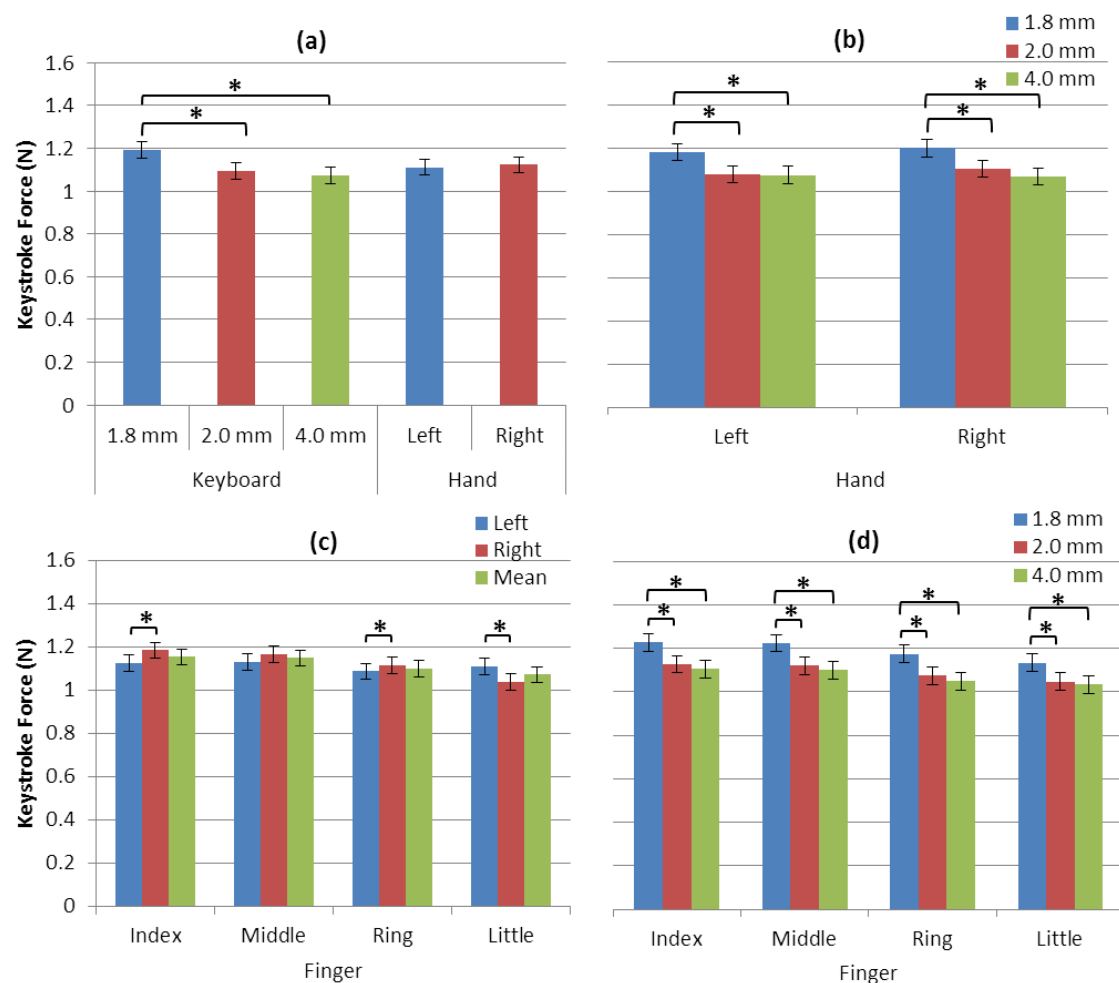


Figure 3.5 Comparisons of mean keystroke forces [n=13]: (a) by keyboard and by hand; (b) by hand and keyboard; (c) by finger and hand; (d) by finger and keyboard. Asterisks denote statistical significance ($p < 0.05$).

3.4. Discussion

Using keyboards with different keyswitch force-displacement characteristics, the present study tested the hypothesis that keystroke durations measured from the keyboard's digital signals approximates those measured from the keystroke force profiles. The results showed that the force-based keystroke durations were strongly associated with software-based durations, supporting our hypothesis that the software-measured keystroke durations derived from the digital signals could be used as a non-invasive, cost-effective, surrogate exposure measure in lieu of the more invasive force measurements. In addition, since small temporal changes in the force-derived keystroke durations are most closely related to the physiological fatigue-based changes in the force output of the muscle, the fact that software-based keystroke durations closely mirrored the force-derived keystroke durations indicates the software-based keystroke durations are also closely tied to physiological, fatigue-based changes in the force output of the muscle.

The results showed that the differences in keystroke durations between keyboards were greater with the software-based measures compared to the force-based measures. This was not surprising since the applied force profiles were not affected by the electromechanical differences in keyswitch designs whereas digital signal durations were dependent on the electromechanical and force-displacement differences across keyboards. Although the software-based keystroke durations appeared to be more dependent on the force-displacement characteristics of the keyboard and therefore different from force-based keystroke durations, the software-based measures demonstrated similar hand- and finger-related differences to force-based keystroke durations. Furthermore, the high correlation between the two different measures (Figure 3.4(b-d)) indicated that the software-based

keystroke durations, with the exception of the small constant bias, closely mirrored the true force-based keystroke durations.

The present study revealed that the force-based keystroke durations from the non-dominant left hand were approximately 10 % longer than those from the dominant right hand on average (Figure 3.3(c)). This hand-related difference in keystroke durations may be due to strength-related differences between hands. Numerous studies have suggested that the dominant hand is significantly stronger than the non-dominant hand (C. A. Armstrong & Oldham, 1999; Crosby & Wehbe, 1994; Petersen, Petrick, Connor, & Conklin, 1989). Given that there were no differences in applied forces between hands ($p = 0.47$), the strength-related differences between hands may have resulted in higher relative load and therefore longer keystroke durations in the weaker non-dominant left hand. Interestingly, this hand-related difference in force-based keystroke durations was also captured by the software-based keystroke durations. This finding also demonstrated that software-based keystroke durations would be a viable surrogate measure for force-based keystroke durations.

The results also demonstrated that there were significant differences among fingers in the force-based keystroke durations ($p < 0.0001$); the keystroke durations from the ring and little fingers were longer than those from index and middle fingers (Figure 3.3(d)). The ring and little fingers are known to be 50 to 60 % of the strengths of the index and middle fingers (Dickson, Nicolle, Calnan, & Petrie, 1972; B. J. Martin et al., 1996; Radwin & Jeng, 1997). The differences in mean keystroke forces between fingers were small (at most, 0.12 N) but statistically significant (Figure 3.5(c)) and paralleled the differences in finger strengths. Given the similar mean keystroke forces and different strengths of fingers, the relative workload on the weaker ring and little fingers would be approximately two-fold greater than

that on the index and middle fingers. This higher relative workload may explain the longer software- and force-based keystroke durations on the weaker ring and little fingers. The software-based keystroke durations not only mirrored the hand-based differences but they also mirrored the finger-related differences in the force-based keystroke durations. This finding may imply that the relative load on fingers during keyboard typing could be optimized by designing key activation forces to be proportional with the respective strengths of the fingers.

The keyboard-related differences in applied finger forces may also be related to force-displacement differences between keyboards. Previous studies showed that the travel distance and key activation forces also affect typing forces (Radwin & Ruffalo, 1999; D. Rempel, Tittiranonda, Burastero, Hudes, & So, 1999). According to Figure 3.1, the 1.8 and 2.0 mm keyboard had a similar activation force (0.6 N) and travel distance to the make point (0.6 mm) whereas 4.0 mm keyboard had longer travel distance to the make point (1.2 mm), less key stiffness (more gradual slope) and a greater overall key travel. Also, the differences in applied finger forces between 1.8 and 2.0 mm keyboard may be due to differences in travel distances or key feel, with the difference being the key feel or the difference in travel distance from the make point and the end of key travel ($T_{1.8}$ and $T_{2.0}$ in Figure 3.1). These differences in the shape of the force-displacement curves may have resulted in the different applied finger forces between the keyboards.

The significant hand by finger interaction in applied finger forces indicated that the finger-related differences in applied forces were more pronounced on the non-dominant hand (Figure 3.5(c)). This may be explained by potential differences in typing biomechanics between the two little fingers. That is, the right little finger has only one designated alphabet

key, p, whereas the left little finger has three keys, a, q, z. Since p key is located in the upper row among the alphabetical keys, biomechanical movements of the right little finger may be different than those from the left little finger where the keystrokes are spread across all three alphabetic rows. Previous studies have shown that finger postures affect finger joint characteristics and therefore determine applied finger forces during keyboard typing (Jindrich et al., 2004a, 2004b; Wu et al., 2008). The postural differences between the right and left little finger may have also contributed to the significant hand by finger interaction. Given the known strength differences among the fingers, the relative applied forces would be highest in the left little finger. This would imply that the left little finger had to exert the greatest relative force and had the greatest difficulty in activating the keys; consequently, it would be reasonable to expect the left little finger to have the longest keystroke durations. In fact, the force-based keystroke durations revealed the hand by finger interactions (Figure 3.3(d)), indicating that the left little finger had disproportionately longer keystroke durations. This phenomenon was also captured by the software-based keystroke durations (Figure 3.3(b)). According to the direct relationships between applied finger force and key activation force discussed in the previous paragraph, the higher relative applied forces of the left little finger could be reduced by adjusting the key activation forces to be proportional to finger strength.

In conclusion, the study findings indicated that software-based keystroke durations derived from the digital signals approximated the true force-derived keystroke durations, independently of the keyswitch force-displacement characteristics. Therefore, the software-based keystroke durations, which can be readily and non-invasively measured by software programs installed on the user's computer, could potentially be used as a surrogate, force-based duration measure in lieu of the more complicated, expensive and invasive force

platform derived measurements. The loss of being able to measure the actual peak and mean force exposures is the limitation of basing keystroke force duration measurements on the keyboard's digital signals, as force-based measures provide important potential interests as a source of feedback to the users (Samani, Holtermann, Sogaard, & Madeleine, 2010). However, the gain is the simplicity, low cost and ability to collect large samples using software-derived keystroke frequency and duration measures for epidemiological purposes. In addition, the study results also indicate that hand- and finger-based differences in keystroke durations and applied finger forces could be minimized by scaling keyboard activation forces to be proportional to some measure of finger strength. This may imply that the current paradigm of designing keyboards with the same fixed activation force for all fingers may not be optimal. Hence, it might also be worthwhile to investigate if adjusting activation forces of individual keys by finger and/or hand strength may be beneficial.

Chapter 4 - Viability of using keystroke and mouse button-click durations to measure muscle fatigue

Abstract

The present study investigated whether intensive keyboard and mouse use resulted in muscle fatigue and whether keystroke and mouse button-click durations systematically changed and paralleled with the temporal changes in muscle twitch durations during exposure and recovery periods. Based on the objective measures of muscle fatigue (the muscle's twitch force response to electrical stimulation), the results indicated that intensive keyboard use, intensive mouse use, and combined intensive mouse and keyboard use all caused muscle fatigue with the different degree of muscle fatigue between the three conditions. An intermediate state of muscle fatigue was observed during, mouse use and combined keyboard and mouse use; keystroke durations systematically changed in these conditions and paralleled the temporal changes in muscle twitch durations. However, the changes in mouse button-click duration did not mirror the temporal changes in muscle twitch durations. The important outcome of this study was documenting that muscle fatigue does result from intensive mouse, keyboard and combined mouse and keyboard use. Intensive mouse use was associated with the greatest levels of muscle fatigue and parallels injury trends seen in the workforce - a greater number and a greater severity of injuries are associated with mouse use. Preliminary results indicate, by monitoring for systematic changes in keystroke duration, we may be able to turn the computer operator's own keyboard into an exposure assessment device which may ultimately reduce computer-related injuries. Using the mouse in a similar fashion was not successful but merits further investigation.

4.1. Introduction

Computer use has been associated with musculoskeletal disorders (Bergqvist et al., 1995; Chang et al., 2009; Fredric Gerr et al., 2002). Although exact underlying mechanisms have not been well understood, muscle fatigue may be a precursor to MSDs (Punnett & Wegman, 2004; D. M. Rempel et al., 1992; Takala, 2002). Muscle fatigue can be identified by monitoring changes in physiological status of the muscle (Figure 4.1). Therefore, an early detection of these physiological changes may help reduce occurrences of computer-related MSDs.

Repeated activation of a muscle initially results in muscle potentiation characterized by increase in twitch force and decrease in contraction and half-relaxation time (Garner et al., 1989; Gossen & Sale, 2000; Green & Jones, 1989; Hamada et al., 2000; Miyamoto et al., 2011; O'leary et al., 1997; Vandervoort et al., 1983) (Figure 4.1). Muscle potentiation can result from both involuntary contractions as a result of subjecting a muscle to electrical stimulation (posttetanic potentiation) contractions and voluntary contractions (postactivation potentiation) as a result of exposing a muscle to physical work (MacIntosh et al., 2006). Potentiation is thought to be due to either the phosphorylation of myosin regulatory light chains (Grange, Vandenboom, & Houston, 1993; Houston, Green, & Stull, 1985; Palmer & Moore, 1989) which increases the sensitivity of myosin heads to Ca^{2+} (Fowles & Green, 2003; Metzger, Greaser, & Moss, 1989; Sweeney & Stull, 1990) or the increased cytosolic Ca^{2+} concentration which facilitates the binding of the contractile proteins (Allen et al., 1989; Green & Jones, 1989). These potentiation-mediated mechanisms are thought to delay the development of muscle fatigue. Because of the protective effects of potentiation combatting the onset and development of muscle fatigue, if the duration of the exercise is short and/or its

intensity is low, the muscle will end up in a state of potentiation (increased force output and a shortened contraction duration) rather than a state of classical muscle fatigue (decreased force output and a lengthened contraction duration).

If the exercise lasts long enough or requires a moderate to high force work, potentiation and fatigue can coexist (Fowles & Green, 2003; Grange & Houston, 1991; Rassier & Macintosh, 2000; Vandervoort et al., 1983). With a combined state of potentiation and fatigue, the muscle twitch force is still elevated (potentiated) but lower compared to when the muscle was in a pure state of potentiation, and muscle twitch duration starts to lengthen (a sign of the onset of muscle fatigue) (Figure 4.1). Eventually, if the exercise is intense enough, muscle fatigue will overcome potentiation and the muscle twitch duration will continue to lengthen and the twitch forces will drop below the pre-exercise levels. Then, in recovery, muscle twitch durations will shorten and the muscle twitch forces will increase and return back to the pre-exercise levels (Figure 4.1). The mechanisms of developing muscle fatigue are discussed in detail in Chapter 1, section 1.2.

Previous studies have shown that subtle, systematic changes in keystroke and mouse button-click durations may be related to the aforementioned physiological changes in the muscle and may be indicative of a computer operator developing muscle fatigue (Chang et al., 2009; Komandur et al., 2008). In Chapter 2 and 3, I showed that software-based keystroke and mouse button-click durations were accurate, sensitive and robust enough to detect small changes. Therefore, software-based keystroke and mouse button-click durations have the potential to be used as surrogate, non-invasive assessment methods to evaluate computer-related muscle fatigue.

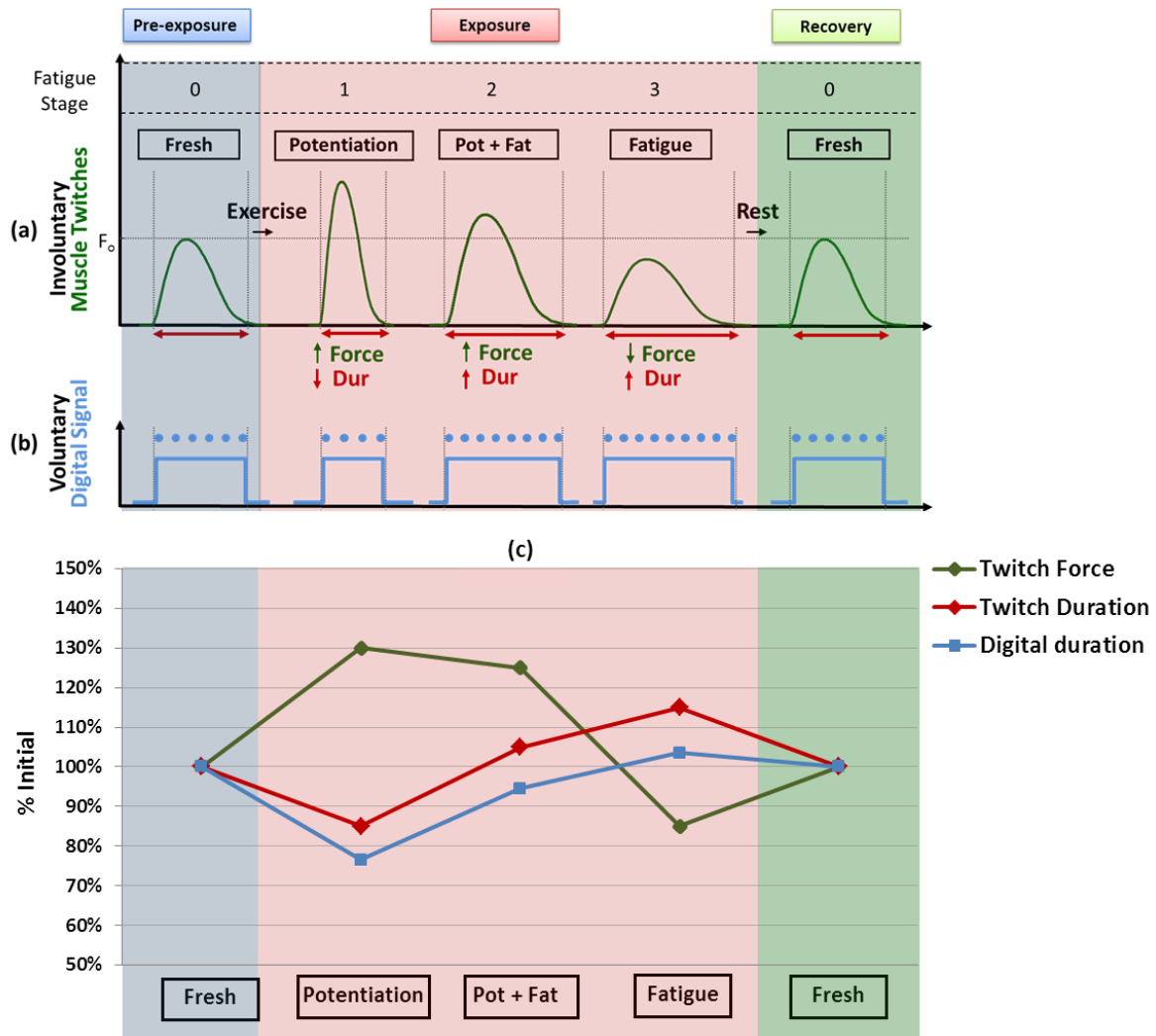


Figure 4.1 To visualize the hypothesis, schematic representation of muscle fatigue: (a) involuntary muscle twitch contractions - fresh (stage 0), potentiated (stage 1), potentiated and fatigued (stage 2) and fatigued (stage 3) muscle twitch; (b) the corresponding voluntary muscle contractions measured with the digital signals from the mouse button or keyboard presented; (c) hypothetical changes in muscle twitch force, twitch duration, and digital signal durations of keystrokes and mouse button clicks.

In the current study, we hypothesized that keystroke durations measured by digital signals from a keyboard (Figure 4.1(b, c)) can reflect physiological changes in the state of the muscle (changes in muscle twitch durations - in Figure 4.1(a)). If changes in durations of the digital signals parallel the durational changes in muscle twitch durations (contraction and half

relaxation time) shown in Figure 4.1(c), the digital signal from a keyboard may be a viable, exposure assessment tool to proactively detect and identify when computer operators may be developing muscle fatigue. Therefore, the ultimate goal of the present study is to determine whether temporal changes in keystroke durations during intensive computer can be used to provide a non-invasive way to identify underlying physiological changes in the state of the muscle (muscle fatigue) and ultimately reduce the computer operator's chances of developing computer-related MSDs.

4.2. Methods

4.2.1 Subjects

Through e-mail solicitations (Appendix A), a total of 18 subjects including 9 males and 9 females were recruited to participate in this experiment. All the participants were right-handed touch-typists without a history of upper extremity MSDs. Their average typing speed was 60.3 words per minute (WPM) (SD 13.2), ranging from 42 to 85 WPM. Their average age was 24.9 years old (SD 4.9), ranging from 21 to 34 years old. The experimental protocol was approved by the Human Subject Committee at the University of Washington, and all subjects provided the written informed consent (Appendix C) before participating in the experiments.

4.2.2 Study design

Using a repeated measures design consisting of four different conditions, all subjects participated in each condition (Figure 4.2). The four eight-hour experimental days consisted of one control day when no task was given and three exposure days (keyboard use, mouse use, and a combined activity consisting of 25% of keyboard and 75% mouse

use) comprising 6 hours of computer use followed by 2 hours of recovery. The order of these four conditions was randomized to minimize potential confounding effects as well as training/learning effects. There were 15-minute breaks in the morning and afternoon and a 30-minute lunch break in the middle of the day. As shown in Figure 4.2, eight measurements were taken to evaluate muscle fatigue. During each of those measurements, subjects were first asked to rate their muscle fatigue (peripheral fatigue - PF) using Borg CR-10 scale and their boredom (central fatigue) using the visual analogue scale (VAS-CF) developed by Lee et al. (1991). The questionnaires were programed by LabVIEW software (Version 2009; National Instruments; Austin, TX, USA) to automate the recording of the subjective measures (See Appendix D and E). Then, to measure voluntary muscle function, subjects performed a finger tapping task with their right middle finger (FT), a standardized typing task (TT) to measure keystroke durations, and a standardized pointing and clicking task (PT) to measure mouse button-click durations. To measure involuntary muscle function, subjects received 2 Hz electrical stimulation to the right middle finger FDS muscle.

Subjective assessment of peripheral (PF) and central fatigue (CF)

Greening and Lynn (1998) found that damage to the soft tissues may begin to accumulated even before people perceive symptoms while Valencia (1986) showed that inhibitory feedback such as discomfort may be a precursor to peripheral muscle fatigue. These contradictory findings imply that self-reported measures may not be sensitive enough to detect underlying physiological changes in the muscle. Subjective measures of peripheral fatigue were used in this experiment to determine how well the subjective measures reflected the objective measures of fatigue obtained from electrical stimulation,

typing, pointing and finger tapping tasks; that is, whether physiological changes occur in the absence or presence of any self-reported discomfort. The questionnaire was designed based on Borg CR-10 scale to measure subjective peripheral muscle fatigue (Appendix D).

As discussed in Chapter 1, however, human movements are controlled by both central (motor cortex, spinal cord, motor neurons, inhibitory reflexes, etc.) and peripheral components (E-C coupling, biochemical changes in muscle fibers, blood flow, etc.). Therefore, it is also important to try to determine whether central factors can influence peripheral muscle fatigue. The central fatigue was evaluated using the VAS-F developed by Lee et al. (1991) (Appendix E).

Finger tapping task (FT)

The finger tapping task, where participants tapped as fast as possible with the right middle finger on a force transducer (Greenleaf Medical Pinch Meter, Palo Alto, CA, USA), involved measuring the voluntary muscle contractile responses of force and contraction duration (contraction time + one-half relaxation time). Because the twitch durations were collected on the right middle finger (see the next section), we chose to collect the finger tapping data from the same finger. This finger tapping task was administered in all four conditions. The finger tapping measures were used to determine whether intensive computer use affected finger muscle contraction durations under voluntary control.

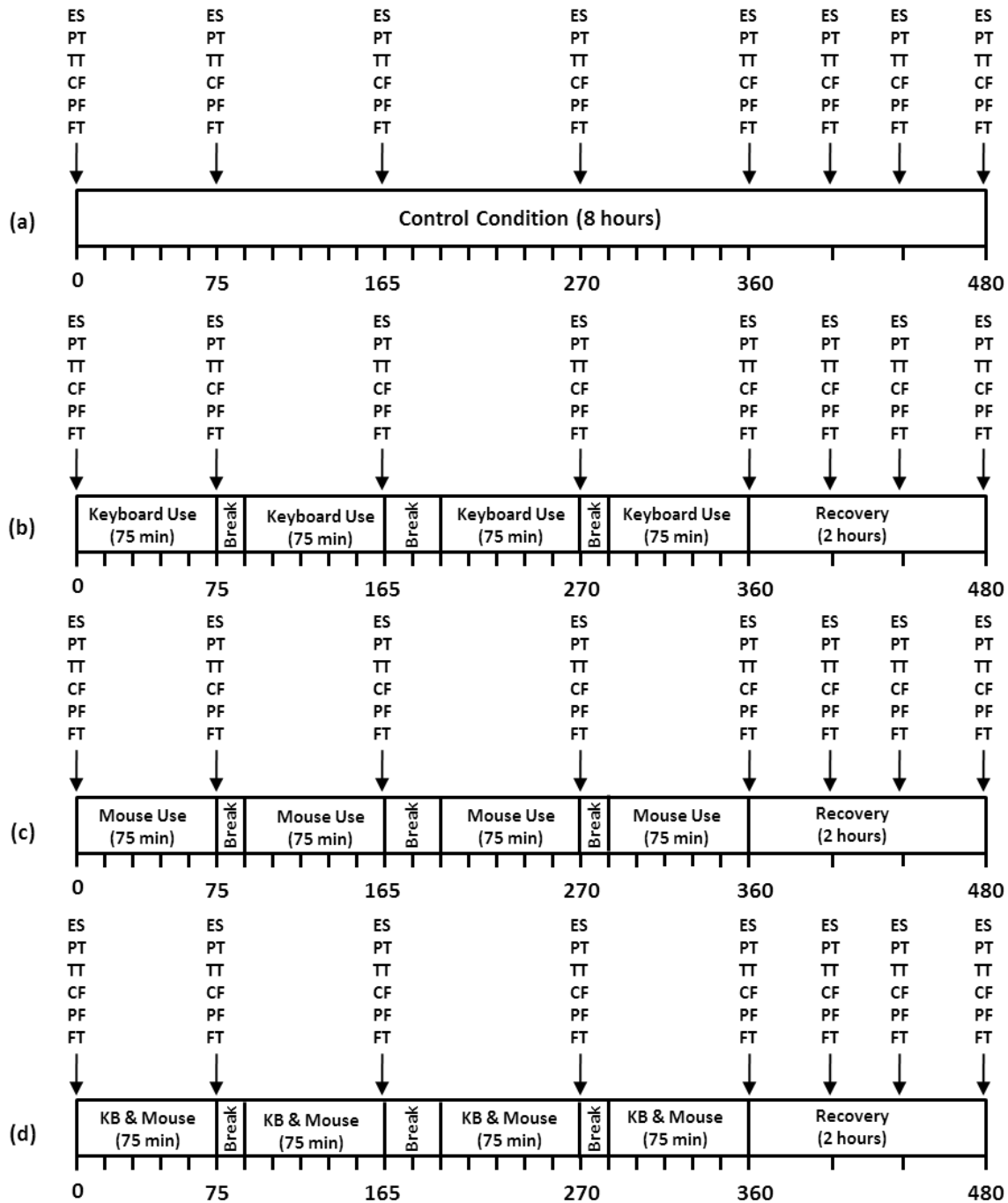


Figure 4.2 Experiment design: (a) control condition, (b) keyboard exposure condition, (c) mouse exposure condition, and (d) the combined mouse and keyboard condition. At the beginning of the experiment, during the breaks and in a two-hour recovery period, the force response of the muscle was measured (ES), a standardized omni-directional pointing task was performed with the mouse (PT), a standardized typing task was performed with the keyboard (TT), a finger tapping task was conducted with the middle finger (FT) and self-reported their peripheral muscle fatigue (PF) and boredom/central fatigue (CF).

Since the finger tapping task is voluntary contraction, changes in the force responses may be affected by both central and peripheral components. Previous studies have demonstrated that the size principle in motor unit recruitment is violated during involuntary contraction evoked by electrical stimulation (R. M. Enoka, 2002; Feiereisen, Duchateau, & Hainaut, 1997; MacIntosh et al., 2006). That is, the recruitment pattern of motor units during involuntary contraction is known to be different from that during voluntary contraction. These differences between voluntary and involuntary contractions may indicate that changes in involuntary contractile measures may not necessarily mirror those in voluntary contractions. Therefore, it is worthwhile to collect force responses from voluntary contractions in order to compare two different contractions. Through the comparison, I evaluated the effects of central factors on change in finger movements.

Standardized typing task (TT)

A standardized typing task was administered using a LabVIEW-based program across all four conditions. In order to control the text which participants typed, I developed a typing program using LabVIEW software (Version 2009; National Instruments; Austin, TX, USA). Since there were 8 typing tasks per day, I created 32 sets of text taken from *Grimm's Fairy Tales*. The sets of text were selected such that the number of right middle finger keys (i's and k's) occurred approximately 20 times during a typical 1-minute typing task (TT). This was done in order to have relatively balanced data sets when changes in keystroke durations in the right middle finger were evaluated across the four conditions. The order of files to be used for the typing task was randomized.

During the typing tasks, keystroke durations were measured by a computer monitoring program developed using LabVIEW software (Version 7.1; National

Instruments; Austin, TX, USA). Keystroke duration was based on the length of the digital ON/OFF signal when subjects pressed and released a key on a keyboard. As demonstrated in Chapters 2 and 3, the computer monitoring program had the requisite resolution needed to detect small changes in keystroke duration. The program registered keystrokes with a resolution of approximately ± 5 ms. Using the keystroke durations measured from the standardized typing task, I determined whether there were changes in the keystroke durations as a function of exposure over time and between the four different conditions.

Standardized omni-directional pointing task (PT)

A standardized omni-directional pointing task was administered using a LabVIEW-based program developed by Han (2006). As shown in Figure 4.3, the omni-directional pointing task consisted of moving and acquiring/clicking on 18 circular targets arranged in a circle. A subject would move the mouse to position the cursor over the highlighted circular target, click on it, and the circular target would disappear. This task continued until all 18 circular targets were acquired. During the pointing task, the computer monitoring program collected mouse button-click durations and was used to determine whether there were changes in the mouse button-click durations as a function of exposure and between the four different conditions. Also, temporal changes in the mouse button-click durations were compared to the corresponding muscle twitch durations evoked with the electrical stimulation to the muscle. Since the muscle twitch durations were collected from the right middle finger (see the next section), in order to compare the voluntary and involuntary finger muscle contraction, the mouse was programmed so subjects operated the right mouse button with their right middle finger (rather than the left button with their index finger).

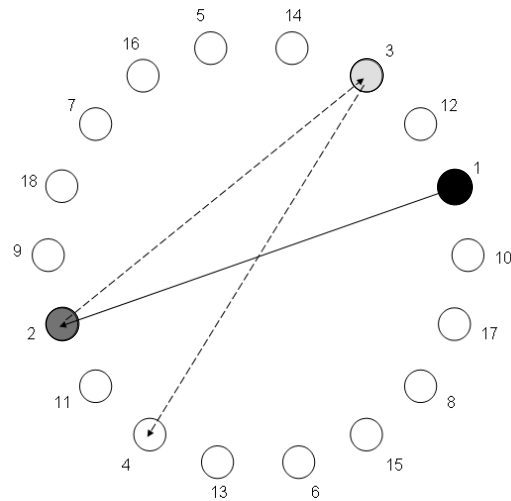


Figure 4.3 Schematic representation of the omni-directional pointing task

Electrical stimulation method (ES)

The low frequency electrical stimulation method developed by Johnson (Peter Wallace Johnson, 1998) was used to objectively measure muscle fatigue in FDS muscle of the right middle finger at the beginning of the experiment, during the breaks, and in the two-hour recovery period. As shown in Figure 4.4, muscle twitches of subject's FDS were evoked by 2 Hz electrical stimulation controlled with a S48 stimulator, SIU5 stimulus isolation unit and CCU-1 constant current unit (Grass Instruments, W. Warwick, RI, USA). During the electrical stimulation, middle finger twitch forces and twitch durations (contraction + one-half relaxation time) were recorded at the rate of 5000 Hz using the force transducer (Greenleaf Medical Pinch Meter, Palo Alto, CA, USA) connected to a National Instruments data acquisition device (NI USB-6259 BNC; National Instruments Corporation; Austin; Texas).

On an orientation day prior to the four experiment days, the optimal location for administering electrical stimulation to the right middle finger FDS muscle was identified

by moving two Ag-AgCl flat tip probes (Model: E208; In Vivo Metric, Healdsburg, CA, USA), with a 20-mm center-to-center probe spacing, over the muscle belly until the muscle's force response reached maximal with isolated movements within the middle finger. Although the right index finger is the predominant finger used during regular mouse operations, the right middle finger was chosen to activate the mouse button and be stimulated because the index finger's FDS muscle is too deep to be stimulated using surface electrodes. Once the optimal sites for the right middle finger FDS muscle were identified, the subject's maximum tolerable stimulation intensity was determined by gradually increasing the current until the level of subject's pain reached at six on a zero to ten pain scale (Hanchard, Williamson, Caley, & Cooper, 1998). The stimulation duration was 100 μ s and the current ranged from 10 to 30 milliamps (Figure 4.4).

On the experiment days, subject's skin over the electrical stimulation site was prepared by cleaning with Alcohol Prep Pads (Dynarex, Orangeburg, NY, USA); then two Ag-AgCl surface electrodes (Model: Blue Sensor N; Ambu; Ballerup, Denmark) were placed on the muscle with a center-to-center of 20 mm between the two electrodes (Figure 4.4). During electrical stimulation measurement, the FDS muscle was preconditioned with 2 Hz continuous electrical stimulation for 90 seconds (Adamo et al., 2009; Adamo et al., 2002; Bennie et al., 2002; Chang et al., 2009; Peter Wallace Johnson, 1998; Peter W Johnson & Crenshaw, 2009; Lin, 2005). While the five 15-twitch trains of electrical stimulations were being administered, the muscle's force responses were measured. Objective measures of the muscle's force responses included twitch force, contraction time, and one-half relaxation time (Figure 4.4(e)). The measures allowed us to investigate whether changes in the muscle twitch measures paralleled the temporal changes in

keystroke and mouse button-click durations (measured from PT and TT), and voluntary contraction measures (obtained from FT).

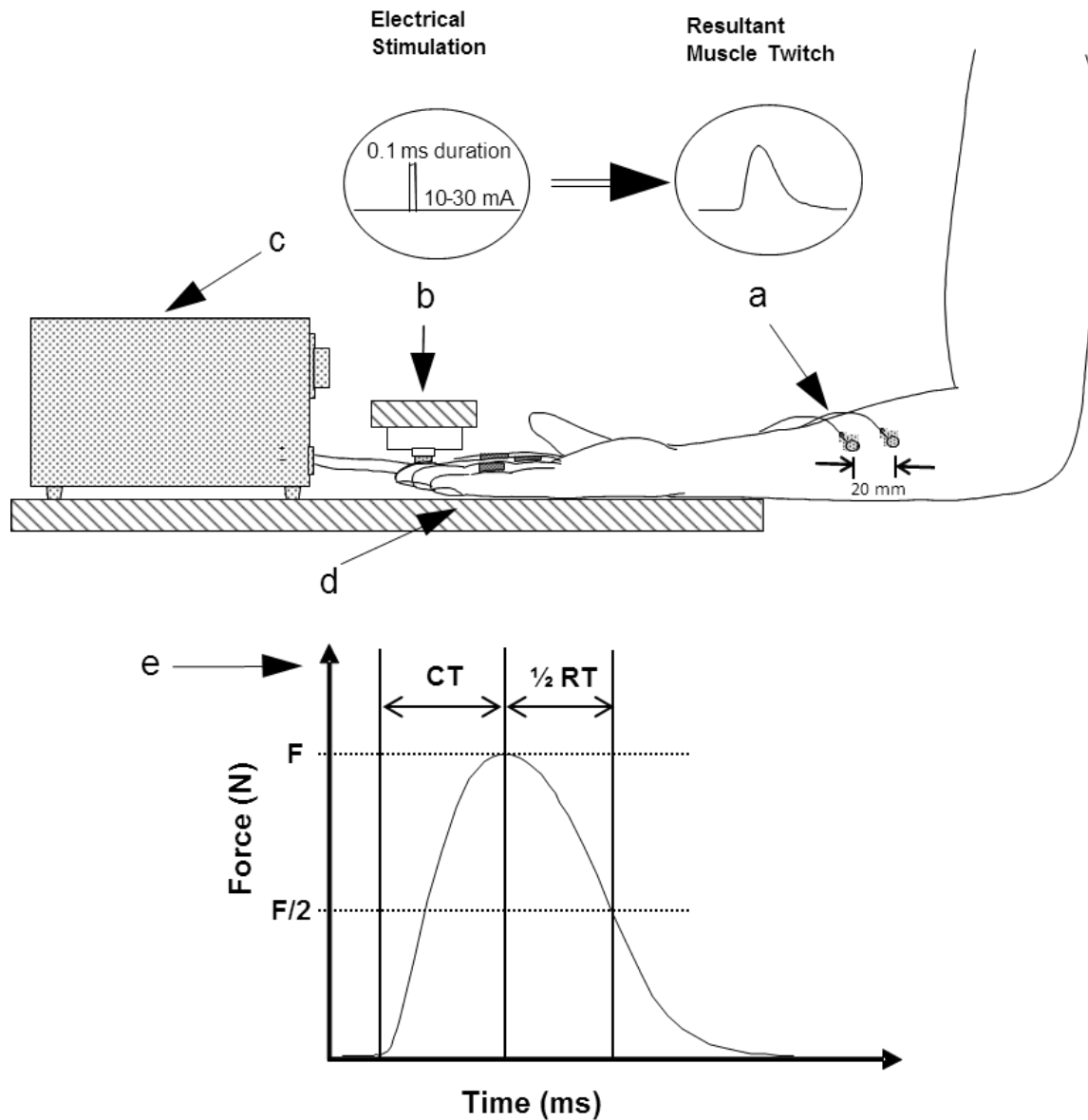


Figure 4.4 Diagram of the twitch measurement apparatus as seen from the side and twitch force measure: (a) surface electrodes over FDS; (b) force transducer over the middle finger; (c) electrical stimulator; (d) restraining jig; (e) twitch force profile – F(twitch force), CT(contraction time), and $\frac{1}{2}$ RT(one-half relaxation time). Inserts show the electrical stimulation and the resultant muscle twitch. Modified with permission from Johnson (1998).

Experimental Conditions

Condition 1 – Control Day

Control condition was administered to obtain baseline measures so that I can determine how the three different conditions above are different from the control condition. This control condition allowed us to account for the natural variability in the physiological status without computer use. In addition, the control condition enabled me to determine whether the electrical stimulation method itself caused temporal physiological changes.

Condition 2 - Standardized keyboard use

Keyboard use was considered a fatiguing exercise. Although previous studies showed that keystroke durations changed in a presence of muscle fatigue (Chang et al., 2009), unrealistic exercise (15% or 30 % of MVC) was used to fatigue the muscles rather than actual typing tasks. In this study, I wanted to use a realistic fatiguing exercise, keyboard typing. Similar to the typing task (TT), a standardized typing task was administered using a LabVIEW-based program on the keyboard use day. Subjects were asked to type chapters of Grimm's Fairy Tale at their normal typing speed for four 75-minute blocks. All subjects were given the same chapters but the order of chapters was randomized in order to minimize any learning or memorization effects. Before, during and after the keyboard use, the typing task (TT) and pointing task (PT) were used to measure keystroke and mouse button-click durations, respectively. These longitudinal measures of keystroke durations enabled me to determine whether rapid and repetitive finger movements during keyboard typing cause muscle fatigue and whether the present study results are consistent with previous findings.

Condition 3 - Standardized mouse use

While primary risk factors of keyboard typing are rapid and repetitive movement, mouse use cause static loading on the finger muscles. As discussed earlier, previous epidemiologic studies have shown that mouse use has stronger association with MSDs. Hence, this laboratory study investigated whether 6 hours of mouse operation caused muscle fatigue. Subjects were asked to use the mouse for four 75-minute blocks. To strike a balance between boredom and providing a standardized task for subjects to perform, participants were asked to play the card game Solitaire on the computer. Before, during and after the mouse use, mouse button-click and keystroke durations were measured with the pointing task (PT) and typing task (TT), respectively. These longitudinal measures of mouse button click durations allowed me to determine whether static loading on forearm muscles during mouse use causes physiological changes.

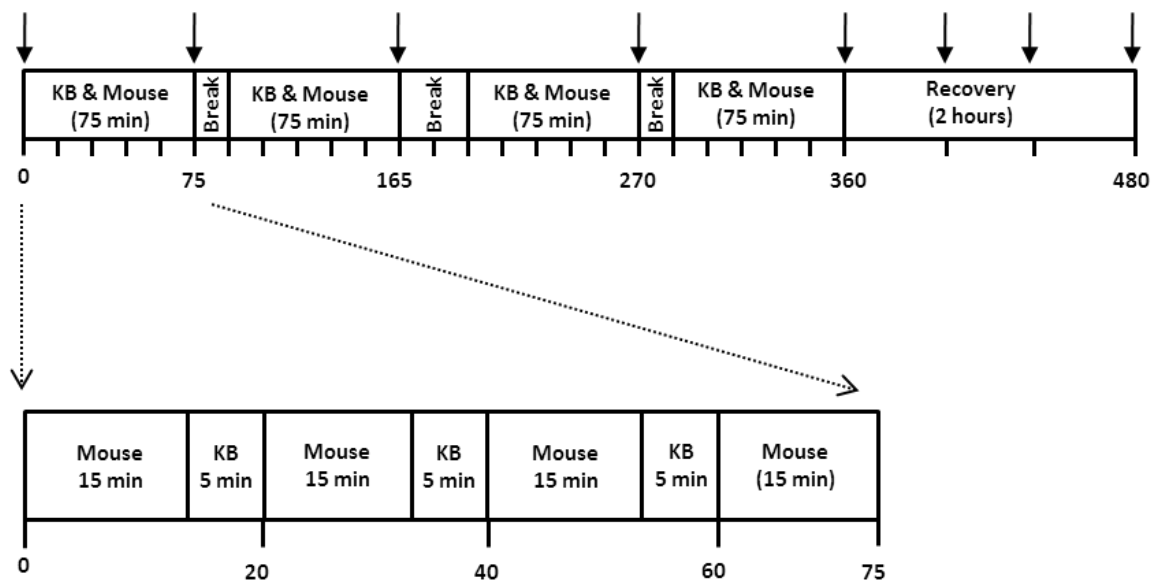


Figure 4.5 Design of the combined keyboard and mouse use

Condition 4 - Standardized combination of keyboard and mouse use

The two conditions described above allowed us to investigate whether keyboard and/or mouse use was associated with muscle fatigue. However, those conditions may not accurately represent realistic computer use since both keyboard and mouse are used in normal computer operations. In this condition, during each 75-minute session, subjects were asked to alternate between playing Solitaire for 15 minutes and typing for 5 minute (Figure 4.5). The proportion of keyboard and mouse use was determined based on previous studies (Chang, Johnson, & Dennerlein, 2008; Hanson-Risberg, Rempel, Hagberg, Karlqvist, & Wilgaeus Hjelm, 1994; Peter Wallace Johnson, 1998). Before, during and after the session of combined mouse and keyboard use, the typing task (TT) and pointing task (PT) were used to measure keystroke and mouse button-click durations, respectively. Comparing these data with those measured from other conditions, I was able to study the effects that the different tasks had on the onset and development of muscle fatigue.

4.2.3 Data analysis

Before analyzing the data, the keystroke duration data were screened to only include ballistic keystrokes associated with the alphabetical keys, since other keys such as space, shift, control, alt, numeric and functional keys might have different or non-ballistic key activations. Furthermore, keystroke durations longer than 250 ms were also excluded since this is the key roll-over duration in Windows (where a key sends multiple keystrokes when the key is held down).

The statistical analysis was conducted in JMP (Version 8.0.2; SAS Institute Inc.; Cary, NC, USA). A *mixed model with restricted maximum likelihood estimation (REML)* was be used to determine whether there were differences in group means. In the model,

subject was included as a random effect; the exposure condition and time were the fixed effects. For the follow-up comparisons, *Dunnett's* tests were used to determine whether there were any differences between the baseline measures and any of the subsequent seven measurement periods which spanned the 8 hours of each experiment. *Friedman* test and post-hoc multiple comparisons in R (R 2.13.2, Development Core Team) were used to determine the effect of intensive computer use on subjective measures of central and peripheral fatigue. Significance was noted when Type I error is less than 0.05.

4.3. Results

4.3.1 Control Condition

In the control condition, FDS muscle twitch forces at 75 and 165 minutes were approximately 10% higher than their initial pre-exposure measure ($p = 0.02$ and 0.04 , respectively). Despite the 10% increase, the muscle twitch force changes were relatively stable in the control condition compared to other exposure conditions (Figure 4.6). The muscle twitch durations (contraction time + $\frac{1}{2}$ relaxation time), keystroke durations, and finger tapping durations did not vary over the seven measurement periods compared to their initial measures at baseline (0 min); in contrast, the mouse button-click duration systematically shortened with time over the duration of the experiment ($p < 0.0001$).

Subjective peripheral fatigue measures (PF) in the hand, wrist, forearm, shoulder, and neck did not differ from their initial responses whereas subjective central fatigue (CF) measured at 480 minutes was higher ($p = 0.003$) than its initial value (Figure 4.7).

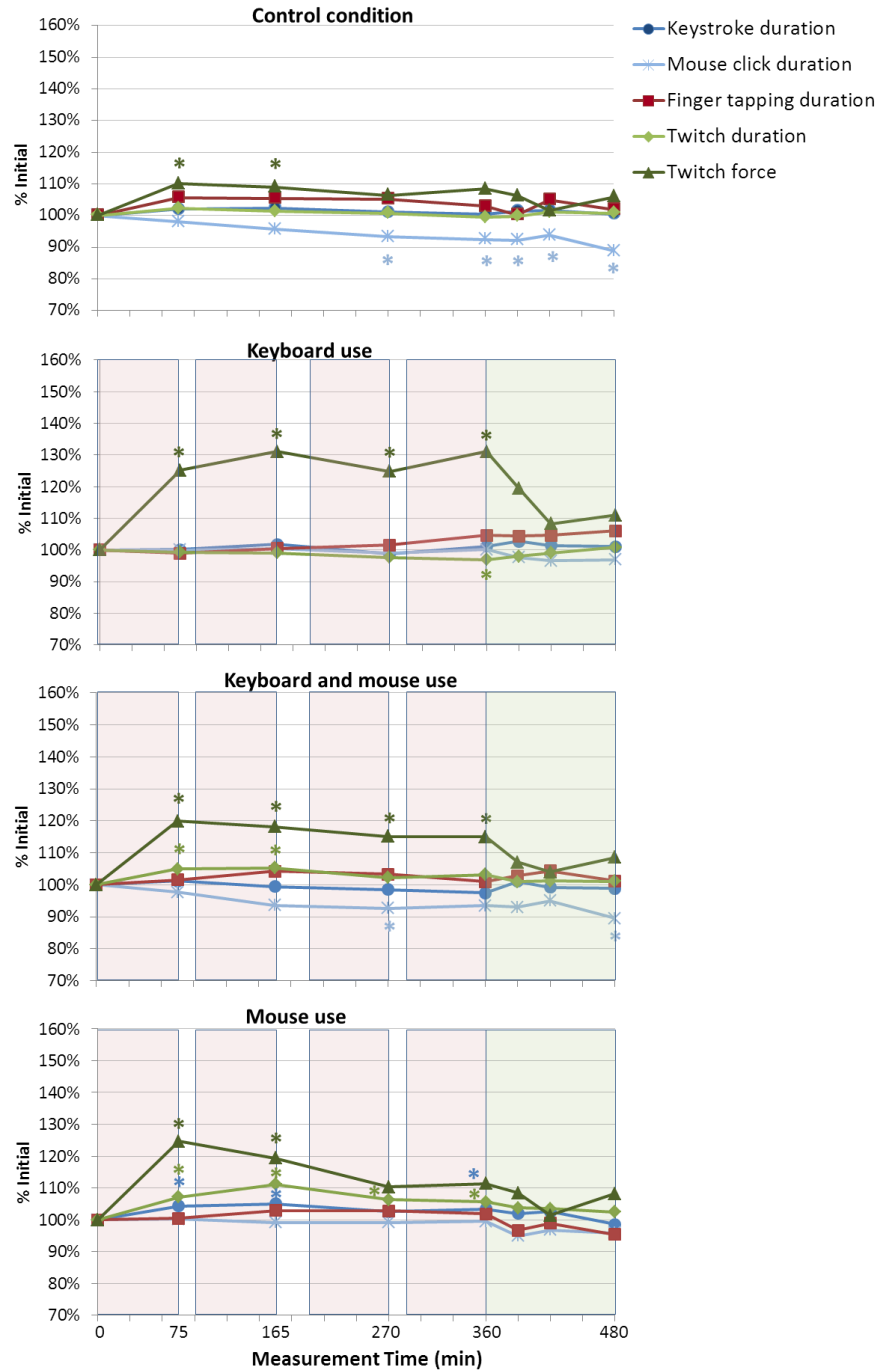


Figure 4.6 Changes in keystroke, mouse button-click, finger tapping durations (voluntary contractions), and muscle twitch durations (involuntary contractions) and the muscle twitch forces in the four different conditions [n = 18]. Red shaded columns indicate 75-minute blocks of exposure time (keyboard and/or mouse use), white columns indicate the rest time between blocks (15, 30, and 15 minutes respectively) and the green shaded columns indicate the two-hour recovery period. All the values normalized by the initial values at time 0. Asterisks denote statistical significance ($p < 0.05$). The standard error bars are excluded for clarity.

4.3.2 Keyboard use

FDS muscle twitch forces measured just after the four 75-minute typing sessions increased approximately 25 to 31% compared to the initial value measured prior to keyboard use (p 's < 0.01); then the twitch forces decreased and returned towards baseline levels during the 2-hour recovery period (Figure 4.6). In contrast, the muscle twitch durations showed a descending trend and decreased by 3% (3.1 ms) at 360 minutes ($p = 0.04$); then, the durations gradually recovered in the recovery period. Keystroke, mouse button-click, and finger tapping durations did not change significantly in the keyboard condition.

Subjective peripheral fatigue in the hand, wrist, forearm, shoulder, and neck significantly increased (p 's < 0.0001) during the four 75-minute blocks of keyboard use (Figure 4.7). Subjective fatigue levels decreased in the recovery period but remained above baseline levels. Similarly, central fatigue significantly increased (p 's < 0.0001) during the 6-hour exposure periods (Figure 4.7) and then recovered to its initial level at the end of the experiment.

4.3.3 Mouse use

After the first 75-minutes of mouse use, muscle twitch force increased approximately 25% ($p = 0.002$); then, gradually declined with time during the remaining three blocks of mouse use (Figure 4.6). Muscle twitch durations lengthened and remained elevated during the exposure period (p 's < 0.001) and returned to baseline levels during the 2-hour recovery period. Keystroke durations also lengthened and remained elevated during mouse use with the keystroke durations being significantly longer after three of the four 75 minute mousing sessions (p 's < 0.03) and returned to baseline levels during the 2-hour recovery period. The

mouse button-click durations and finger tapping durations did not change with time during and after mouse use.

Subjective peripheral fatigue levels systematically increased during the 6-hour exposure periods (p 's < 0.0001) and returned towards baseline levels but remained elevated during the 2-hour recovery period (Figure 4.7). Similarly, central fatigue significantly increased (p 's < 0.0001) during the four 75-minute blocks of mouse use (Figure 4.7) and then recovered to its initial level at the end of the experiment.

4.3.4 Keyboard and Mouse use

During combined keyboard and mouse use, muscle twitch forces increased approximately 15 to 20% relative to the initial pre-exposure measures (p 's < 0.007) and then returned toward baseline levels in the 2-hour recovery period (Figure 4.6). Muscle twitch durations were significantly longer after the first two 75-minute blocks of combined keyboard and mouse use compared to the initial pre-exposure measures (p 's < 0.01), gradually declined during the last two blocks of the exposure periods and then returned to baseline levels in the 2-hour recovery period. Keystroke and finger tapping durations did not show any significant changes with respect to time in the combined keyboard and mouse use condition; however, the mouse button-click duration systematically shortened ($p < 0.003$).

Subjective peripheral and central fatigue significantly increased (p 's < 0.0001) during the 6 hours of the combined keyboard and mouse use (Figure 4.7). Central and peripheral fatigue levels returned towards baseline levels, except for peripheral fatigue in the right hand and wrist.

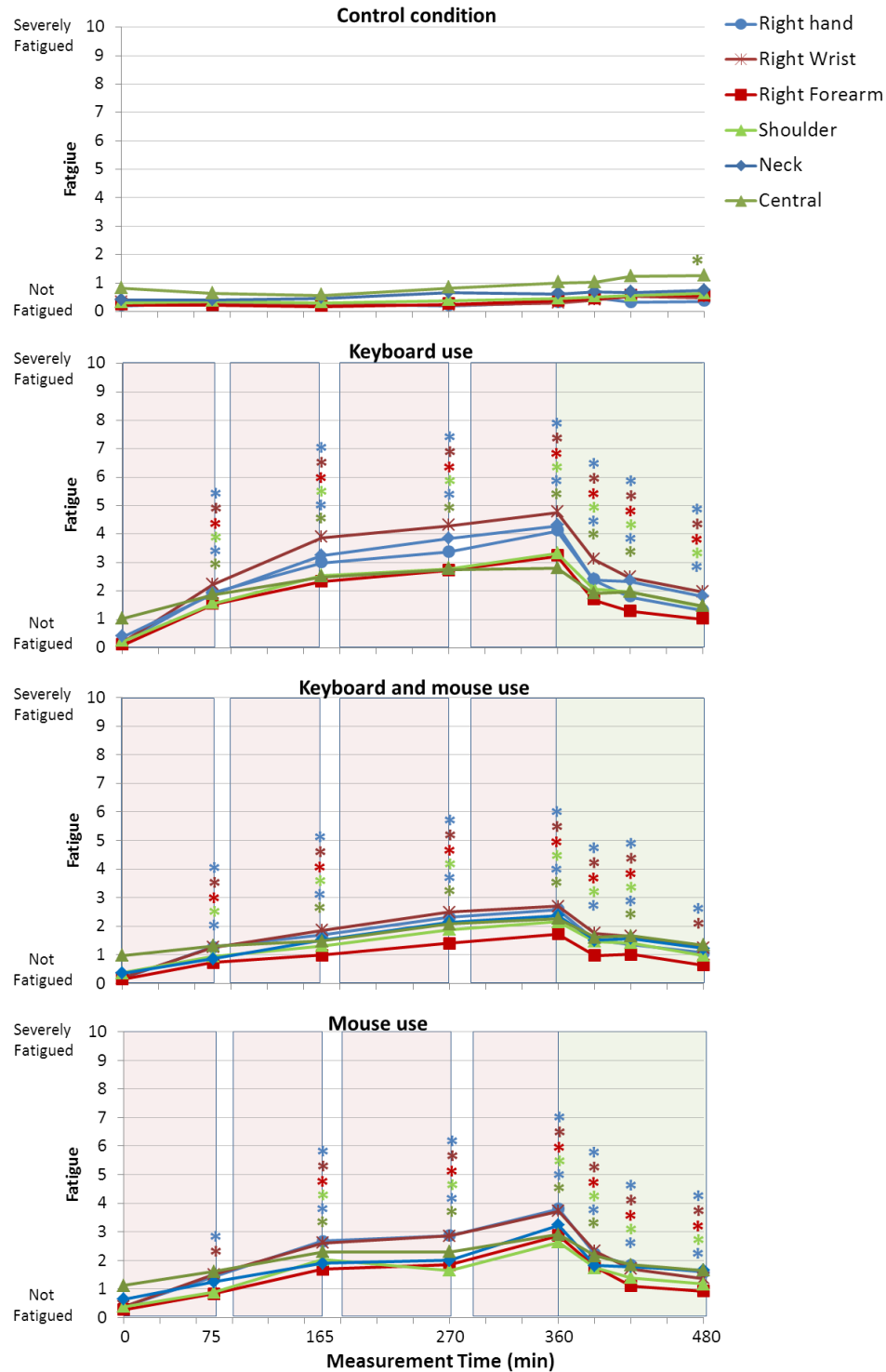


Figure 4.7 Changes subjective peripheral and central fatigue measures [n = 18]. Shaded columns (red) indicate 75-minute blocks of exposure time (keyboard or mouse use), the rest time between the blocks were 15, 30, and 15 minutes respectively including two hours of recovery (green shaded) at the end after keyboard use had ceased. Asterisks denote statistical significance at $\alpha = 0.05$. The standard error bars are excluded for the clarification.

4.4. Discussion

The present study was conducted to determine whether there were systematic changes in keystroke and/or mouse button-click durations with six hours of intensive keyboard use which paralleled objective voluntary and involuntary changes in the physiological state of the muscle measured during voluntary (a standardized typing, mousing and finger tapping test) and involuntary (electrical stimulation of the muscle) activities. The results indicated that intensive keyboard use, intensive mouse use, and combined intensive mouse and keyboard use all caused muscle fatigue; however, differing stages of muscle fatigue were observed. This study also found that, when the changes in the muscle twitch durations were large enough, the systematic changes in the keystroke duration paralleled those of the muscle twitches.

4.4.1 Control condition

As expected, involuntary (twitch), voluntary (finger tapping), and keystroke durations did not change over time in the control condition when there was no physical exposure. However, twitch forces increased by 10% relative to baseline measures. This increased twitch force could have been due to the electrical stimulation or related to simple diurnal changes caused by a gradual increase in the subjects' muscle temperature over the course of the experiment. Involuntary muscle contraction by electrical stimulation can induce muscle potentiation (Chang et al., 2009; Peter Wallace Johnson, 1998; MacIntosh et al., 2006), and its initial response is increased contraction force. Johnson (1998) and Chang et al. (2009) also showed that electrical stimulation could affect physiological response of muscle such as contraction force and/or duration.

Although there was lack of physiological changes in the control condition, mouse button-click duration systematically shortened throughout the day. This may be due to limitations of the simulated pointing task used to collect mouse button-click durations or actual diurnal changes possibly associated with increases in muscle temperature. As described in Figure 4.3, the targets were highlighted sequentially, so participants were able to predict where the next target will be and accordingly prepare the next movements to click the following targets. The predictability may have resulted in learning effects; therefore the mouse button-click durations systematically shortened. The systematic shorting caused by the potential learning effects were also found in the combined keyboard and mouse condition as well as the recovery periods of keyboard use and mouse use. In future studies, therefore, it would be beneficial to randomize the order with which the targets appears or craft a realistic mousing task in order to determine whether changes in the mouse button-click duration mirror those in the twitch duration. More importantly, when muscle temperatures increase, the muscle contracts faster (Bennett, 1985; De Ruiter & De Haan, 2000; He, Bottinelli, Pellegrino, Ferenczi, & Reggiani, 2000). No systematic shorting in mouse button-click duration were seen in the keyboard and mouse use conditions, so relative to the control condition, the mouse button click duration lengthened in the keyboard and mouse conditions which would support that the mouse button-click response was different in the exercise conditions. Therefore, changes in mouse button click merits further investigation as they did appear to be systematic difference but these changed did not mirror the keystroke and mouse button-click durations.

4.4.2 Keyboard use

In the condition involving six hours of intensive keyboard use, muscle twitch durations systematically shortened whereas muscle twitch forces significantly increased. As described in Figure 4.1, early-stage muscle fatigue (stage 1) could be characterized by an increase in the force output of the muscle and a shortening of the muscle's contraction duration (potentiation). The results indicated that dynamic muscle contractions from repetitive finger movements during typing on the keyboard caused the early-stage muscle fatigue.

Although the twitch durations shortened, keystroke durations did not change. The twitch duration was measured from the involuntary contraction evoked by electrical stimulation on the FDS muscle bypassing the central nerve system. In contrast, the keystroke duration was measured from the voluntary finger movement which is likely to be affected by peripheral and central components as well as other muscles such as finger extensor. Given these differences, 3% (3.1 ms) change on FDS muscle twitch duration may be difficult to be captured by the keystroke duration. Numerous studies have shown the potential differences between the voluntary and involuntary contractions (R. M. Enoka, 2002; Feiereisen et al., 1997; MacIntosh et al., 2006).

The muscle twitch responses showed that intensive keyboard use resulted in early-stage muscle fatigue. However, subjective peripheral fatigue measures were disproportionally high given that the muscle just in an early-stage of muscle fatigue. Previous studies (Greening & Lynn, 1998; Valencia, 1986) have shown that the subjective sense of peripheral fatigue is not necessarily synchronized with its objective measure. Even low concentrations of metabolites produced by muscle contraction could increase blood pressures in the muscle (Alam & Smirk, 1937). Sensory afferents could detect both the

contraction-produced metabolites and increase blood pressure in the muscle; consequently, the sensation of muscle fatigue could increase (Light, Vierck, & Light, 2010). At this early stage, the muscle twitch force and duration may not be affected by the low concentration of metabolites. This argument can be supported by a previous study (Valencia, 1986) finding that subjective muscle discomfort preceded the measurement of peripheral muscle fatigue.

4.4.3 Mouse use

After the first 75-minute session of intensive mouse use, both muscle twitch force and duration significantly increased, indicating the coexistence of muscle potentiation and fatigue (as described in Figure 4.1). In the remaining three 75-minute blocks of mouse use, the twitch force systematically decreased over time (Figure 4.6) while twitch durations remained elevated. As described in Figure 4.1 (a), the twitch force decreases below baseline levels while the twitch duration remains lengthened, when the muscle is on a path to go from fatigue stage 2 to fatigue stage 3. This finding demonstrated that the physiological muscle status was transitioning from the potentiation and fatigue to the conventional fatigue status during the mouse use.

During the four blocks of mouse use, the increase in keystroke durations paralleled the temporal increases in muscle twitch durations. Despite the inherent differences between the voluntary and involuntary contractions, the keystroke duration may have been able to capture physiological changes in the muscle due to the greater changes in twitch duration. This result is consistent with a previous study where the muscle was moderately fatigued (Chang et al., 2009) and the changes in keystroke durations paralleled the temporal changes in muscle twitch durations. This implies that temporal changes in keystroke duration may be used to detect conventional muscle fatigue.

The results showed that the temporal changes in muscle twitch force and duration during mouse use were different from those during keyboard use. The twitch data showed that keyboard use resulted in the early-stage muscle fatigue (stage 1) whereas the mouse use induced more severe state muscle fatigue (stage 2). This finding supports previous study findings that the mouse use is more highly associated with MSDs, compared to keyboard use (S. Ijmker et al., 2007). Although those studies have argued that prolonged static load and longer usage duration may increase the association between mouse use and MSDs (Andersen et al., 2003; Jensen, 2003; Kryger et al., 2003; Lassen et al., 2004), there has been lack of physiological evidence to objectively justify the argument. This study result may provide some physiological evidence to help explain the different MSDs association between keyboard and mouse.

4.4.4 Keyboard and mouse use

In the combined intensive keyboard and mouse condition, the muscle fatigue was between the fatigue levels measured during keyboard use (early-stage fatigue) and mouse use (intermediate-stage fatigue). As observed in the keyboard condition (Figure 4.6), the muscle twitch forces significantly increased and remained elevated compared to baseline measurements. Similar to the changes in the mouse condition, the muscle twitch durations also increased in the combined keyboard and mouse condition. The magnitude and trend of changes in twitch force and duration (Figure 4.6) showed that the level of muscle fatigue was between early and intermediate fatigue state, between the fatigue observed in intensive keyboard and mouse use conditions, respectively.

Each 75-minute block in the combined keyboard and mouse use condition consisted of 60-minutes mouse use interleaved with 15-minutes of keyboard use (Figure 4.5). This is

the ratio of mouse to keyboard use which occurs during occupational computer work. Although the majority of the exposure was mouse operation, the fatigue level during the combined mouse and keyboard condition was not as pronounced as what was measured during the exclusive mouse condition. The intermediate level of fatigue may be due to the variation in muscle loading created by switching between mouse and keyboard use. Since monotonous and repetitive tasks are well-known risk factors for muscle fatigue and MSDs (S. Ijmker et al., 2007; Peter Wallace Johnson, 1998; Tayyari & Smith, 1997), task variation is thought to be one of the most effective administrative ergonomic interventions (Tayyari & Smith, 1997). The mixture of two different increased the task variability and the resultant variability in muscle load; therefore, more severe muscle fatigue was prevented.

Although the combined mouse and keyboard use resulted a significant lengthening of the muscle twitch durations, keystroke durations did not show any parallel temporal changes. This may be due to relatively small changes in muscle twitch durations (5%, 5.5 ms), compared to the greater relative changes in mouse condition (11%, 11.3 ms). As discussed earlier, due to the inherent differences between the involuntary muscle twitch and voluntary keystroke durations, keystroke durations may only be able to detect temporal fatigue-related changes in muscle twitch durations when the changes are reasonably large. Despite the minimal changes in the muscle twitch and keystroke durations, the mouse button-click duration systematically shortened over time (Figure 4.6). As discussed in the control condition, this inconsistency could be explained by actual diurnal changes possibly associated with increased muscle temperature and/or the limitation of the data collection methods.

Subjective peripheral and central fatigue significantly increased. However, the level of fatigue was lower than that observed in the other two exposure conditions. Furthermore, most subjective fatigue measures in this condition recovered to the baseline level at the end of the experiment except for the right and wrist, whereas in the other two exposure conditions, the perception of fatigue persisted throughout the 2-hour recovery period. The lower levels of perceived fatigue and the nearly complete restitution in the 2-hour recovery period are likely the result of the greater task variability. Higher variability during the combined mouse and keyboard use condition may have reduced monotonousness, repetitiveness, and boredom while increasing posture variability; consequently, the level of the subjective central and peripheral fatigue was lower, compared to the exclusive keyboard or mouse use conditions.

4.4.5 Conclusion

The current study demonstrated that changes in muscle twitch durations were detected by the keystroke durations when changes in muscle twitch durations were large (intermediate-stage muscle fatigue), supporting the hypothesis that, when the fatigue is of an intense enough level, keystroke durations measured by digital signals can reflect physiological changes in the state of the muscle. Since the keystroke duration can be readily and non-invasively measured by software programs installed on the user's computer, it could be used as a non-invasive way to identify muscle fatigue and ultimately reduce the computer operator's chances of developing computer-related MSDs.

The results also showed that the level of muscle fatigue during mouse use was higher compared to keyboard use. This finding supports the previous findings that the mouse use is more strongly associated with MSDs than the keyboard use. Therefore, this finding can

provide physiological evidence which may help explain the different MSDs association between keyboard and mouse use.

Chapter 5 - Conclusions and future work

5.1. Summary

The present study investigated whether intensive computer use induced any physiological changes in the FDS muscle and whether those physiological changes were captured by the temporal changes in keystroke and/or mouse button-click durations. Previous studies have shown that subtle, systematic changes in keystroke durations (Chang et al., 2009) and mouse button-click durations (Komandur et al., 2008) corresponded with the temporal changes in physiological status of the muscle and therefore may be used as a surrogate exposure assessment tool to measure muscle fatigue during computer use. However, both of these prior studies have limitations which were addressed in this dissertation. In the study by Chang et al. (2009), two 15-minute submaximal contraction conditions at 15% (static exercise) and 30% (dynamic exercise) of MVC respectively were used to fatigue the right ring finger FDS muscle. However, muscle contractions required to activate the keys on a keyboard or a mouse button is much less than the force levels used by Chang (Chang et al., 2009; Dennerlein, Diao, Mote, & Rempel, 1998; Peter Wallace Johnson, 1998; Radwin & Jeng, 1997; D. Rempel et al., 1994; D. Rempel et al., 1997); typically between 0.4% and 10% MVC, therefore, their fatiguing exercise was unrealistic. In addition, although Komandur et al. (2008) demonstrated that mouse button-click durations may be a surrogate measure of muscle twitch durations, they only measured at one point in time and did not investigate the temporal changes in the button-click durations which may parallel changes in muscle twitch durations during prolonged computer use.

This study investigated whether any physiological changes in the muscle status were caused by the actual computer use and whether these temporal physiological changes in the muscle mirrored similar trends in keystroke and mouse button-click durations. The results of the present study showed that the subtle, systematic changes in keystroke duration mirrored the temporal changes in the muscle twitch durations in the presence of a moderate muscle fatigue. Therefore, software-measured keystroke durations may be a viable non-invasive assessment tool to detect temporal physiological changes (i.e. muscle fatigue) during computer use.

Before testing the main hypotheses, in Chapter 2, I first validated the accuracy of the computer monitoring program against an external USB signal analyzer (gold standard) for measuring the duration of the digital signals used to calculate keystroke durations. The results showed that the computer monitoring program provided enough accuracy and sensitivity to detect small changes in keystroke durations (down to a few milliseconds) and therefore could be used as an accurate, viable measurement tool. Although mouse button click durations were not explicitly tested in Chapter 2, the digital signals would be handled the same way and the accuracy and errors should be similar to the trends found with the keystroke durations.

Although the software-measured keystroke duration provides enough accuracy and sensitivity to detect and measure small changes in keystroke durations, the software-measured keystroke duration may be affected by the electromechanical and force-displacement characteristics of keyboards. Therefore, in Chapter 3 by comparing the software-based keystroke duration measures to the force-based keystroke duration measures (gold standard – independent of any keyboard characteristics), I was able to determine

whether the software-based keystroke durations were affected by the different electromechanical and force-displacement characteristics. The results indicated that the software-based keystroke durations were affected by the different keyboard characteristics but the affect was a systematic bias (constant offset). Despite the bias, the small across-time and between-subject difference in keystroke durations were captured and mirrored the true force-derived across-time and between subject differences in keystroke durations.

Chapters 4 determined whether muscle fatigue developed in the right ring flexor digitorum superficialis (FDS) muscle during intensive keyboard, intensive mouse and combine intensive mouse and keyboard use by using the low frequency electrical stimulation method developed by Johnson (1998) and used in previous studies (Adamo et al., 2009; Adamo et al., 2002; Bennie et al., 2002; Chang et al., 2009; Peter Wallace Johnson, 1998; Peter W Johnson & Crenshaw, 2009; Lin, 2005). The results found that muscle fatigue resulted from intensive keyboard, mouse, and combined keyboard and mouse use; however, different levels of muscle fatigue were observed. I also investigated whether keystroke and mouse button-click duration changed in the presence of muscle fatigue and whether the temporal changes in electrical stimulation measures corresponded with the temporal changes in keystroke and mouse button-click durations. The results indicated that the systematic, temporal changes in the keystroke durations mirrored the temporal changes in muscle twitch durations when the computer work resulted in a moderate level of muscle fatigue. Using the mouse button-click in a similar fashion was not successful but merits further investigation due to the potential limitation associated with the data collection method (discussed in Chapter 4).

5.2. Contributions

MSDs are the single largest component of occupational injuries, accounting for 40% of all injuries and therefore are the most common and costly injuries in office work environments (Lyon, 1992; Punnett & Wegman, 2004). Computer use has been associated with MSDs since many of risk factors for developing MSDs such as force, repetitiveness, postures, and monotonousness are encountered during computer work (Chang et al., 2009; F. Gerr et al., 2006). Although intensive computer use has been associated with MSDs, the association between computer use and MSDs has long been debated. Amongst main reasons for this longstanding debate is that the exposure-response relationship between computer use and MSD-related injuries are not fully understood. Developing an adequate, non-invasive, cost-effective, exposure assessment method for large scale epidemiological studies on computer use could contribute to the body of knowledge on the potential underlying injury mechanisms. Furthermore, since most work-related MSDs develop from the accumulation of micro trauma to the soft tissues (muscles, tendons, ligaments and nerves) over time (Punnett & Wegman, 2004), proactive detection of physiological degradation (i.e. muscle fatigue) will be merited.

There are several lab-based methods to measure muscle fatigue such as electrical stimulation of the muscle, electromyography and mechanomyography; however, these methods may be suitable only in lab-based studies due to invasiveness, portability and cost. Furthermore, it may be difficult to measure temporal physiological changes during computer use since computer work must be interrupted to use those methods. Therefore, it is desired to develop a non-invasive method to evaluate muscle fatigue during computer use. Although

there have been some attempts to develop a non-invasive assessment tool, those attempts have been incomprehensive.

The present study results showed that the keystroke duration identified fatigue-related physiological changes in the FDS muscle when the computer work resulted in moderate levels of muscle fatigue. Since the subtle, systematic changes in keystroke duration were related to the fatigue-related physiological changes in the finger muscle, by measuring changes in the keystroke durations, the computer program I developed may detect computer-related muscle fatigue and proactively notify computer users of their fatigue, thereby reducing their chances of developing computer-related MSDs. The keystroke duration can readily be measured by a computer program installed on users' computers; therefore, temporal systematic changes in keystroke durations could be used as a surrogate, non-invasive, cost-effective measure to indicate muscle fatigue.

The previous studies have shown that a greater number and severity of injuries and symptoms are associated with the mouse use, as compared to keyboard use. However, most studies have not been able to provide any physiological evidence to explain the different associations other than the assumptions that the prolonged static loading on muscle and longer usage duration may increase the association between mouse use and MSDs (Andersen et al., 2003; Jensen, 2003; Kryger et al., 2003; Lassen et al., 2004). As this study found that the mouse use was associated with the greatest levels of muscle fatigue, this physiological evidence corroborates previous findings that the mouse use is more strongly associated with computer-related MSDs, compared to the keyboard use.

5.3. Limitations

Although I tried to avoid any potential limitations, it is rare to have a perfectly designed experiment and some limitations still remained in the present study. All the tasks during computer use were standardized so that the muscle fatigue effects between subjects could be compared. However, the standardized tasks used in this study may not represent realistic computer work. Solitaire, a card game preinstalled in Windows XP, was used as a task during mouse use to investigate the muscle fatigue between subjects. This task was specifically chosen to strike a balance between creating a standardized task and minimizing the resultant boredom from performing a standardized task over a six hour period. The intensive, exclusive mouse use was likely different from the activities engaged in during actual computer work. Exclusive, intensive typing may also not be a realistic task given how subjects use both the mouse and keyboard to work at the computer. As a result of these concerns, a combined keyboard and mouse use task was developed where mouse and keyboard tasks were partitioned such that subjects performed those two different tasks in a serial, alternating manner (Figure 4.5). However, even this task has limitations, since during real computer use, mouse and keyboard are used in a more simultaneous, parallel manner as needed. In future studies, therefore, these standardized tasks could be substituted with actual computer work to determine whether muscle fatigue is also developed during actual work.

Simulated pointing tasks were administered to collect mouse button-click durations. As described in Figure 4.3, the targets were highlighted sequentially, so participants were able to predict where the next target would appear. As discussed in Chapter 5, the non-random sequence of the target movement may have distorted the mouse button-click durations over time; consequently, the mouse button-click durations did not reflect the twitch duration

changes. Therefore, further investigation may be merited by randomizing the order with which the targets appears or crafting a more realistic standardized mousing task in order to determine whether the temporal changes in the mouse button-click duration mirror the temporal changes in the muscle twitch durations.

A final limitation was, instead of using the right index finger to activate the left mouse button, which occurs during regular mouse operation, left mouse button was remapped to the right mouse button and the right middle finger was used to perform the mouse button clicking. This was done since the right index finger's muscles are too deep to be activated with our electrical stimulation technique. Therefore, to be able to expose a finger to both typing and mouse button clicking and measure the force response of the muscle to electrical stimulation, the right middle finger had to be tested. However, since the strength of right middle finger is known to be similar to that of index fingers (Dickson et al., 1972; B. J. Martin et al., 1996), muscle fatigue measured in the right middle finger may reasonably approximate to that in right index finger.

References

- Adamo, D. E., Khodaei, M., Barringer, S., Johnson, P. W., & Martin, B. J. (2009). Low mean level sustained and intermittent grip exertions: Influence of age on fatigue and recovery. *Ergonomics*, 52(10), 1287-1297. doi: 10.1080/00140130902984935
- Adamo, D. E., Martin, B. J., & Johnson, P. W. (2002). Vibration-induced muscle fatigue, a possible contribution to musculoskeletal injury. *European Journal of Applied Physiology*, 88(1-2), 134-140. doi: 10.1007/s00421-002-0660-y
- Alam, M., & Smirk, F. H. (1937). Observations in man upon a blood pressure raising reflex arising from the voluntary muscles. *Journal of Physiology-London*, 89(4), 372-383.
- Allen, D. G., Lee, J. A., & Westerblad, H. (1989). Intracellular calcium and tension during fatigue in isolated single muscle fibres from *Xenopus laevis*. *J Physiol The Journal of Physiology*, 415, 433-458.
- Andersen, J. H., Thomsen, J. F., Overgaard, E., Lassen, C. F., Brandt, L. P. A., Vilstrup, I., . . . Mikkelsen, S. (2003). Computer use and carpal tunnel syndrome - A 1-year follow-up study. *Jama-Journal of the American Medical Association*, 289(22), 2963-2969.
- Andries, F., Smulders, P., & Dhondt, S. (2002). The use of computers among the workers in the European Union and its impact on the quality of work. *Behaviour and Information Technology*, 21(6), 441-447.
- Armstrong, C. A., & Oldham, J. A. (1999). A comparison of dominant and non-dominant hand strengths. *Journal of Hand Surgery-British and European Volume*, 24B(4), 421-425.
- Armstrong, T. J., Foulke, J. A., Martin, B. J., Gerson, J., & Rempel, D. M. (1994). Investigation of applied forces in alphanumeric keyboard work. *American Industrial Hygiene Association Journal*, 55(1), 30-35.
- Barker, A. T., & Jalinous, R. (1985). Non-invasive magnetic stimulation of human motor cortex. *Lancet*, 1(8437), 1106-1107.
- Basmajian, J. V., & De Luca, C. J. (1985). *Muscles alive : their functions revealed by electromyography*. Baltimore: Williams & Wilkins.
- Belanger, A. Y., & McComas, A. J. (1981). Extent of motor unit activation during effort. *Journal of Applied Physiology*, 51(5), 1131-1135.
- Bennett, A. F. (1985). Temperature and muscle. *The Journal of experimental biology*, 115, 333-344.
- Bennie, K. J., Ciriello, V. M., Johnson, P. W., & Dennerlein, J. T. (2002). Electromyographic activity of the human extensor carpi ulnaris muscle changes with exposure to repetitive ulnar deviation. *European Journal of Applied Physiology*, 88(1-2), 5-12. doi: 10.1007/s00421-002-0666-5
- Bergqvist, U., Wolgast, E., Nilsson, B., & Voss, M. (1995). The influence of VDT work on musculoskeletal disorders. *Ergonomics*, 38(4), 754-762.
- Biglandritch, B., Furbush, F., & Woods, J. J. (1986). Fatigue of intermittent submaximal voluntary contraction - central and peripheral factors. *Journal of Applied Physiology*, 61(2), 421-429.

- Biglandritchie, B., Jones, D. A., Hosking, G. P., & Edwards, R. H. T. (1978). Central and peripheral fatigue in sustained maximum voluntary contractions of human quadriceps muscle. *Clinical Science and Molecular Medicine*, 54(6), 609-614.
- Blangsted, A. K., Hansen, K., & Jensen, C. (2004). Validation of a commercial software package for quantification of computer use. *International Journal of Industrial Ergonomics*, 34(3), 237-241. doi: 10.1016/j.ergon.2004.04.003
- Blatter, B. M., & Bongers, P. M. (2002). Duration of computer use and mouse use in relation to musculoskeletal disorders of neck or upper limb. *International Journal of Industrial Ergonomics*, 30(4-5), 295-306.
- Bongers, P. M., Ijmker, S., van den Heuvel, S., & Blatter, B. M. (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), 279-302. doi: 10.1007/s10926-006-9044-1
- Burke, A., & Peper, E. (2002). Cumulative Trauma Disorder Risk for Children Using Computer Products: Results of a Pilot Investigation with a Student Convenience Sample. *Public Health Reports*, 117, 350-357.
- Byström, S., & Kilbom, Å. (1991). Electrical stimulation of human forearm extensor muscles as an indicator of handgrip fatigue and recovery. *European journal of applied physiology and occupational physiology*, 62(5), 363-368.
- Cairns, S. P., Taberner, A. J., & Loiselle, D. S. (2009). Changes of surface and t-tubular membrane excitability during fatigue with repeated tetani in isolated mouse fast- and slow-twitch muscle. *Journal of Applied Physiology*, 106(1), 101-112. doi: 10.1152/japplphysiol.90878.2008
- Caputo, C., Edman, K. A. P., Lou, F., & Sun, Y. B. (1994). Variation in myoplasmic Ca^{2+} concentration during contraction and relaxation studied by the indicator fluo-3 in frog-muscle fibers. *Journal of Physiology-London*, 478(1), 137-148.
- Chaffin, D. B. (1973). Localized muscle fatigue--definition and measurement. *Journal of occupational medicine. : official publication of the Industrial Medical Association*, 15(4), 346-354.
- Chang, C. H., Amick, B. C., Menendez, C. C., Katz, J. N., Johnson, P. W., Robertson, M., & Dennerlein, J. T. (2007). Daily computer usage correlated with undergraduate students' musculoskeletal symptoms. *American Journal of Industrial Medicine*, 50(6), 481-488. doi: 10.1002/ajim.20461
- Chang, C. H., Johnson, P. W., & Dennerlein, J. T. (2008). A Wide Range of Activity Duration Cutoffs Provided Unbiased Estimates of Exposure to Computer Use. *Journal of Occupational and Environmental Hygiene*, 5(12), 790-796. doi: 10.1080/15459620802491158
- Chang, C. H., Johnson, P. W., Katz, J. N., Eisen, E. A., & Dennerlein, J. T. (2009). Typing keystroke duration changed after submaximal isometric finger exercises. *European Journal of Applied Physiology*, 105(1), 93-101. doi: 10.1007/s00421-008-0878-4
- Chin, E. R., Balnave, C. D., & Allen, D. G. (1997). Role of intracellular calcium and metabolites in low-frequency fatigue of mouse skeletal muscle. *American Journal of Physiology-Cell Physiology*, 272(2), C550-C559.

- Christensen, H. (1986). Muscle-activity and fatigue in the shoulder muscles during repetitive work - an electromyographic study. *European Journal of Applied Physiology and Occupational Physiology*, 54(6), 596-601.
- Clayton, D. A., & Griffith, C. J. (2004). Observation of food safety practices in catering using notational analysis. *British Food Journal*, 106(3), 211-227.
- Cooke, R., Franks, K., Luciani, G. B., & Pate, E. (1988). The inhibition of rabbit skeletal-muscle contraction by hydrogen-ions and phosphate. *Journal of Physiology-London*, 395, 77-97.
- Cooke, R., & Pate, E. (1985). The effects of ADP and phosphate on the contraction of muscle-fibers. *Biophysical Journal*, 48(5), 789-798.
- Crosby, C. A., & Wehbe, M. A. (1994). Hand strength - normative values. *Journal of Hand Surgery-American Volume*, 19A(4), 665-670.
- Davis, J. M. (1995). Carbohydrates, branched-chain amino-acids, and endurance - the central fatigue hypothesis. *International Journal of Sport Nutrition*, 5, S29-S38.
- De Ruiter, C. J., & De Haan, A. (2000). Temperature effect on the force/velocity relationship of the fresh and fatigued human adductor pollicis muscle. *Pflügers Archiv-European Journal of Physiology*, 440(1), 163-170. doi: 10.1007/s004240000284
- Dennerlein, J. T., Diao, E., Mote, C. D., & Rempel, D. M. (1998). Tensions of the flexor digitorum superficialis are higher than a current model predicts. *Journal of Biomechanics*, 31(4), 295-301.
- Dennerlein, J. T., & Johnson, P. W. (2006). Different computer tasks affect the exposure of the upper extremity to biomechanical risk factors. *Ergonomics*, 49(1), 45-61. doi: 10.1080/00140130500321845
- Devries, H. A. (1968). Method for evaluation of muscle fatigue and endurance from electromyographic fatigue curves. *American Journal of Physical Medicine*, 47(3), 125-&.
- Dickson, R. A., Nicolle, F. V., Calnan, J. S., & Petrie, A. (1972). Device for measuring force of digits of hand. *Biomedical Engineering*, 7(6), 270-&.
- Donaldson, S. K. B., & Hermansen, L. (1978). Differential, direct effects of H^+ on Ca^{2+} - activated force of skinned fibers from soleus, cardiac and adductor magnus muscles of rabbits. *Pflügers Archiv-European Journal of Physiology*, 376(1), 55-65.
- Edman, K. A. P., & Lou, F. (1992). Myofibrillar fatigue versus failure of activation during repetitive stimulation of frog-muscle fibers. *Journal of Physiology-London*, 457, 655-673.
- Edman, K. A. P., & Mattiazzi, A. R. (1981). Effects of fatigue and altered pH on isometric force and velocity of shortening at zero load in frog-muscle fibers. *Journal of Muscle Research and Cell Motility*, 2(3), 321-334.
- Edwards, R. G., & Lippold, O. C. J. (1956). The relation between force and integrated electrical activity in fatigue muscle. *Journal of Physiology-London*, 132(3), 677-681.
- Edwards, R. H. (1981). Human muscle function and fatigue. *Ciba Foundation symposium*, 82, 1-18.
- Edwards, R. H. T., Hill, D. K., Jones, D. A., & Merton, P. A. (1977). Fatigue of long duration in human skeletal muscle after exercise. *The Journal of physiology*, 272(3), 769-778.
- Enoka, R. M. (2002). Activation order of motor axons in electrically evoked contractions. *Muscle & Nerve*, 25(6), 763-764. doi: 10.1002/10117

- Enoka, R. M. (2002). *Neuromechanics of human movement*. Champaign, IL: Human Kinetics.
- Enoka, R. M., & Stuart, D. G. (1992). Neurobiology of muscle fatigue. *Journal of Applied Physiology*, 72(5), 1631-1648.
- Esposito, F., Orizio, C., & Veicsteinas, A. (1998). Electromyogram and mechanomyogram changes in fresh and fatigued muscle during sustained contraction in men. [Article]. *European Journal of Applied Physiology*, 78(6), 494-501.
- Fambrough, D. M., Wolitzky, B. A., Tamkun, M. M., & Takeyasu, K. (1987). Regulation of the sodium-pump in excitable cells. *Kidney International*, 32, S97-S112.
- Feiereisen, P., Duchateau, J., & Hainaut, K. (1997). Motor unit recruitment order during voluntary and electrically induced contractions in the tibialis anterior. *Experimental Brain Research*, 114(1), 117-123.
- Fitts, R. H., & Balog, E. M. (1996). Effect of intracellular and extracellular ion changes on E-C coupling and skeletal muscle fatigue. *Acta Physiologica Scandinavica*, 156(3), 169-181.
- Fowles, J. R., & Green, H. J. (2003). Coexistence of potentiation and low-frequency fatigue during voluntary exercise in human skeletal muscle. *Canadian Journal of Physiology and Pharmacology*, 81(12), 1092-1100. doi: 10.1139/y03-114
- Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews*, 81(4), 1725-1789.
- Garner, S. H., Hicks, A. L., & McComas, A. J. (1989). Prolongation of twitch potentiating mechanisms throughout muscle fatigue and recovery. *Experimental Neurology*, 103(3), 277-281.
- Gerard, M. J., Armstrong, T. J., Foulke, J. A., & Martin, B. J. (1996). Effects of key stiffness on force and the development of fatigue while typing. *American Industrial Hygiene Association Journal*, 57(9), 849-854.
- Gerard, M. J., Armstrong, T. J., Franzblau, A., Martin, B. J., & Rempel, D. M. (1999). The effects of keyswitch stiffness on typing force, finger electromyography, and subjective discomfort. *American Industrial Hygiene Association Journal*, 60(6), 762-769.
- Gerr, F., & Fethke, N. (2011). Ascertaining computer use in studies of musculoskeletal outcomes among computer workers: differences between self-report and computer registration software. *Occupational and Environmental Medicine*, 68(7), 465-466. doi: 10.1136/oemed-2011-100116
- Gerr, F., Marcus, M., Ensor, C., Kleinbaum, D., Cohen, S., Edwards, A., . . . Monteilh, C. (2002). A prospective Study of Computer Users: I. Study Design and Incidence of Musculoskeletal Symptoms and Disorders. *American Journal of Industrial Medicine*, 41, 221-235.
- Gerr, F., Monteilh, C. P., & Marcus, M. (2006). Keyboard use and musculoskeletal outcomes among computer users. *Journal of Occupational Rehabilitation*, 16(3), 265-277. doi: 10.1007/s10926-006-9037-0
- Gossen, E. R., & Sale, D. G. (2000). Effect of postactivation potentiation on dynamic knee extension performance. *European Journal of Applied Physiology*, 83(6), 524-530.
- Grange, R. W., & Houston, M. E. (1991). Simultaneous potentiation and fatigue in quadriceps after a 60-second maximal voluntary isometric contraction. *Journal of Applied Physiology*, 70(2), 726-731.

- Grange, R. W., Vandenboom, R., & Houston, M. E. (1993). Physiological significance of myosin phosphorylation in skeletal-muscle. *Canadian Journal of Applied Physiology- Revue Canadienne De Physiologie Appliquee*, 18(3), 229-242.
- Green, H. J., & Jones, S. R. (1989). Does post-tetanic potentiation compensate for low-frequency fatigue. *Clinical Physiology*, 9(5), 499-514.
- Greening, J., & Lynn, B. (1998). Vibration sense in the upper limb in patients with repetitive strain injury and a group of at-risk office workers. *International Archives of Occupational and Environmental Health*, 71(1), 29-34.
- Hamada, T., Sale, D. G., & Macdougall, J. D. (2000). Postactivation potentiation in endurance-trained male athletes. *Medicine and Science in Sports and Exercise*, 32(2), 403-411.
- Han, C. (2006). *The development of testing software to measure and characterize differences in computer mouse use performance : comparison of adults and children*. Available from <http://worldcat.org/z-dissert/> database.
- Hanchard, N. C. A., Williamson, M., Caley, R. W., & Cooper, R. G. (1998). Electrical stimulation of human tibialis anterior: (A) contractile properties are stable over a range of submaximal voltages; (B) high- and low-frequency fatigue are inducible and reliably assessable at submaximal voltages. *Clinical Rehabilitation*, 12(5), 413-427.
- Hanson-Risberg, E., Rempel, D., Hagberg, M., Karlqvist, L., & Wilgaeus Hjelm, E. (1994). *Inter-method reliability on assessment of duration of visual display terminal work, computer mouse use and working technique*. Paper presented at the 12th Congress of the International Ergonomics Association, Toronto, Canada.
- He, Z. H., Bottinelli, R., Pellegrino, M. A., Ferenczi, M. A., & Reggiani, C. (2000). ATP consumption and efficiency of human single muscle fibers with different myosin isoform composition. *Biophysical Journal*, 79(2), 945-961.
- Heinrich, J., Blatter, B. M., & Bongers, P. M. (2004). A comparison of methods for the assessment of postural load and duration of computer use. *Occupational and Environmental Medicine*, 61(12), 1027-1031. doi: 10.1136/oem.2004.013219
- Hicks, A. L., Kent-Braun, J., & Ditor, D. S. (2001). Sex Differences in Human Skeletal Muscle Fatigue. *Exercise and Sport Sciences Reviews*, 29(3), 109-112.
- Hodgkin, A. L., & Horowicz, P. (1959). The influence of potassium and chloride ions on the membrane potential of single muscle fibers. *Journal of Physiology-London*, 148(1), 127-160.
- Houston, M. E., Green, H. J., & Stull, J. T. (1985). Myosin light chain phosphorylation and isometric twitch potentiation in intact human-muscle. *Pflugers Archiv-European Journal of Physiology*, 403(4), 348-352.
- Hunter, S. K., Critchlow, A., Shin, I.-S., & Enoka, R. M. (2004). Men are more fatigable than strength-matched women when performing intermittent submaximal contractions. *Journal of Applied Physiology*, 96, 2125-2132.
- Hunter, S. K., & Enoka, R. M. (2001). Sex differences in the fatigability of arm muscles depends on absolute force during isometric contractions. *Journal of Applied Physiology*, 91, 2686-2694.
- Hwang, Y. H., Wang, C. H., Liang, H. W., & Luh, J. J. (2009). Validation of a recording system for computer pointing device activity. *International Journal of Industrial Ergonomics*, 39(5), 681-688. doi: 10.1016/j.ergon.2009.01.007

- Ijmker, S., Huysmans, M. A., Blatter, B. M., van der Beek, A. J., van Mechelen, W., & Bongers, P. M. (2007). Should office workers spend fewer hours at their computer? A systematic review of the literature. *Occupational and Environmental Medicine*, 64(4), 211-222. doi: 10.1136/oem.2006.026468
- Ijmker, S., Huysmans, M. A., van der Beek, A. J., Knol, D. L., van Mechelen, W., Bongers, P. M., & Blatter, B. M. (2011). Software-recorded and self-reported duration of computer use in relation to the onset of severe arm-wrist-hand pain and neck-shoulder pain. *Occupational and Environmental Medicine*, 68(7), 502-509. doi: 10.1136/oem.2010.056267
- Ijmker, S., Leijssen, J. N. M., Blatter, B. M., van der Beek, A. J., van Mechelen, W., & Bongers, P. M. (2008). Test-retest reliability and validity of self-reported duration of computer use at work. *Scandinavian Journal of Work Environment & Health*, 34(2), 113-119.
- Jensen, C. (2003). Development of neck and hand-wrist symptoms in relation to duration of computer use at work. *Scandinavian Journal of Work Environment & Health*, 29(3), 197-205.
- Jensen, C., Finsen, L., Sogaard, K., & Christensen, H. (2002). Musculoskeletal symptoms and duration of computer and mouse use. *International Journal of Industrial Ergonomics*, 30(4-5), 265-275.
- Jindrich, D. L., Balakrishnan, A. D., & Dennerlein, J. T. (2004a). Effects of keyswitch design and finger posture on finger joint kinematics and dynamics during tapping on computer keyswitches. *Clinical Biomechanics*, 19(6), 600-608. doi: 10.1016/j.clinbiomech.2004.03.003
- Jindrich, D. L., Balakrishnan, A. D., & Dennerlein, J. T. (2004b). Finger joint impedance during tapping on a computer keyswitch. *Journal of Biomechanics*, 37(10), 1589-1596. doi: 10.1016/j.jbiomech.2004.01.001
- Johnson, P. W. (1998). *The Development, Characterization and Implementation of a Technique to Measure Muscle Fatigue Duration Computer Use*. (Ph.D), University of California, Berkeley.
- Johnson, P. W., & Crenshaw, A. (2009). *Temporal changes in mouse button click duration during fatigue and recovery*. Paper presented at the 17th Triennial Congress of the International Ergonomics Association, Beijing, China.
- Jones, D. A. (1996). High- and low-frequency fatigue revisited. *Acta physiologica Scandinavica*, 156(3), 265-270.
- Juul-Kristensen, B., Sogaard, K., Stroyer, J., & Jensen, C. (2004). Computer users' risk factors for developing shoulder, elbow and back symptoms. *Scandinavian Journal of Work Environment & Health*, 30(5), 390-398.
- Keeton, R. B., & Binder-Macleod, S. A. (2006). Low-frequency fatigue. *Physical Therapy*, 86(8), 1146-1150.
- Komandur, S., Johnson, P. W., & Storch, R. L. (2008). *Relation between mouse button click duration and muscle contraction time*. Paper presented at the 30th Annual International IEEE EMBS Conference, Vancouver, British Columbia, Canada.
- Kryger, A. I., Andersen, J. H., Lassen, C. F., Brandt, L. P. A., Vilstrup, I., Overgaard, E., . . . Mikkelsen, S. (2003). Does computer use pose an occupational hazard for forearm pain; from the NUDATA study. *Occupational and Environmental Medicine*, 60, e14.

- Lassen, C. F., Mikkelsen, S., Kryger, A. I., Brandt, L. P. A., Overgaard, E., Thomsen, J. F., . . . Andersen, J. H. (2004). Elbow and wrist/hand symptoms among 6,943 computer operators: A 1-year follow-up study (The NUDATA study). [Article]. *American Journal of Industrial Medicine*, 46(5), 521-533. doi: 10.1002/ajim.20081
- Lee, J. A., Westerblad, H., & Allen, D. G. (1991). Changes in tetanic and resting $[Ca^{2+}]_i$ during fatigue and recovery of single muscle fibres from *Xenopus laevis*. *The Journal of physiology*, 433, 307-326.
- Lee, K. A., Hicks, G., & Ninomurcia, G. (1991). Validity and reliability of a scale to assess fatigue. *Psychiatry Research*, 36(3), 291-298.
- Lieber, R. L. (2002). *Skeletal muscle structure, function & plasticity : the physiological basis of rehabilitation*. Philadelphia: Lippincott Williams & Wilkins.
- Liepert, J., Kotterba, S., Tegenthoff, M., & Malin, J. P. (1996). Central fatigue assessed by transcranial magnetic stimulation. *Muscle & Nerve*, 19(11), 1429-1434.
- Light, A. R., Vierck, C. J., & Light, K. C. (2010). Myalgia and Fatigue: Translation from Mouse Sensory Neurons to Fibromyalgia and Chronic Fatigue Syndromes *Translational Pain Research: From Mouse to Man*. Boca Raton, FL: CRC Press.
- Lin, Y.-N. (2005). *The effects of high frequency stimulation on fatigue and twitch potentiation*. Available from <http://worldcat.org/z-dissert/> database.
- Lindsley, D. B. (1935). Myographic and electromyographic studies of myasthenia gravis. *Brain*, 58, 470-482.
- Ljubisavljevic, M., Milanovic, S., Radovanovic, S., Vukcevic, I., Kostic, V., & Anastasijevic, R. (1996). Central changes in muscle fatigue during sustained submaximal isometric voluntary contraction as revealed by transcranial magnetic stimulation. *Electromyography and Motor Control-Electroencephalography and Clinical Neurophysiology*, 101(4), 281-288.
- Lyon, B. K. (1992). Video Display Terminal Ergonomics. *PFS Professional Safety*, 37(6), 32-39.
- MacIntosh, B. R., Gardiner, P. F., & McComas, A. J. (2006). *Skeletal muscle : form and function*. Champaign, IL: Human Kinetics.
- Marcus, M., Gerr, F., Monteilh, C., Ortiz, D. J., Gentry, E., Cohen, S., . . . Kleinbaum, D. (2002). A prospective study of computer users: II. Postural risk factors for musculoskeletal symptoms and disorders. [Article]. *American Journal of Industrial Medicine*, 41(4), 236-249. doi: 10.1002/ajim.10067
- Martin, B. J., Armstrong, T. J., Foulke, J. A., Natarajan, S., Klinenberg, E., Serina, E., & Rempel, D. (1996). Keyboard reaction force and finger flexor electromyograms during computer keyboard work. [Article]. *Human Factors*, 38(4), 654-664.
- Martin, V., Millet, G. Y., Martin, A., Deley, G., & Lattier, G. (2004). Assessment of low-frequency fatigue with two methods of electrical stimulation. *Journal of Applied Physiology*, 97, 1923-1929.
- McComas, A. J., Miller, R. G., & Gandevia, S. C. (1995). Fatigue brought on by malfunction of the central and peripheral nervous systems. *Advances in experimental medicine and biology*, 384, 495-512.
- Mellor, R., & Stokes, M. J. (1992). Detection and severity of low frequency fatigue in the human adductor pollicis muscle. *Journal of the Neurological Sciences*, 108(2), 196-201.

- Metzger, J. M., Greaser, M. L., & Moss, R. L. (1989). Variations in cross-bridge attachment rate and tension with phosphorylation of myosin in mammalian skinned skeletal-muscle fibers - implications for twitch potentiation in intact muscle. *Journal of General Physiology*, 93(5), 855-883.
- Mikkelsen, S., Vilstrup, I., Lassen, C. F., Kryger, A. I., Thomsen, J. F., & Andersen, J. H. (2007). Validity of questionnaire self-reports on computer, mouse and keyboard usage during a four-week period. *Occupational and Environmental Medicine*, 64, 541-547.
- Mill, K. R., & Thomson, C. C. B. (1995). Human muscle fatigue investigated by transcranial magnetic stimulation. *Neuroreport*, 6(15), 1966-1968.
- Miller, A. E. J., Macdougall, J. D., Tarnopolsky, M. A., & Sale, D. G. (1993). Gender differences in strength and muscle-fiber characteristics. *European Journal of Applied Physiology and Occupational Physiology*, 66(3), 254-262.
- Miyamoto, N., Yanai, T., & Kawakami, Y. (2011). Twitch potentiation induced by stimulated and voluntary isometric contractions at various torque levels in human knee extensor muscles. *Muscle & Nerve*, 43(3), 360-366. doi: 10.1002/mus.21871
- Nosek, T. M., Fender, K. Y., & Godt, R. E. (1987). It is diprotonated inorganic-phosphate that depresses force in skinned skeletal-muscle fibers. *Science*, 236(4798), 191-193.
- Oleary, D. D., Hope, K., & Sale, D. G. (1997). Posttetanic potentiation of human dorsiflexors. *Journal of Applied Physiology*, 83(6), 2131-2138.
- Palmer, B. M., & Moore, R. L. (1989). Myosin light chain phosphorylation and tension potentiation in mouse skeletal-muscle. *American Journal of Physiology*, 257(5), C1012-C1019.
- Pascarelli, E. F., & Kella, J. J. (1993). Soft-tissue injuries related to use of the computer keyboard - a clinical-study of 53 severely injured persons. *Journal of Occupational and Environmental Medicine*, 35(5), 522-532.
- Petersen, P., Petrick, M., Connor, H., & Conklin, D. (1989). Grip strength and hand dominance - challenging the 10-percent rule. *American Journal of Occupational Therapy*, 43(7), 444-447.
- Punnett, L., & Wegman, D. H. (2004). Work-related musculoskeletal disorders: the epidemiologic evidence and the debate. *Journal of Electromyography and Kinesiology*, 14(1), 13-23. doi: 10.1016/j.jelekin.2003.09.015
- Radwin, R. G., & Jeng, O. J. (1997). Activation force and travel effects on overexertion in repetitive key tapping. *Human Factors*, 39(1), 130-140.
- Radwin, R. G., & Ruffalo, B. A. (1999). Computer key switch force-displacement characteristics and short-term effects on localized fatigue. *Ergonomics*, 42(1), 160-170.
- Rassier, D. E., & Macintosh, B. R. (2000). Coexistence of potentiation and fatigue in skeletal muscle. *Brazilian Journal of Medical and Biological Research*, 33(5), 499-508.
- Rempel, D., Dennerlein, J., Mote, C. D., & Armstrong, T. (1994). A method of measuring fingertip loading during keyboard use. *Journal of Biomechanics*, 27(8), 1101-1104.
- Rempel, D., Serina, E., Klinenberg, E., Martin, B. J., Armstrong, T. J., Foulke, J. A., & Natarajan, S. (1997). The effect of keyboard keyswitch make force on applied force and finger flexor muscle activity. *Ergonomics*, 40(8), 800-808.

- Rempel, D., Tittiranonda, P., Burastero, S., Hudes, M., & So, Y. (1999). Effect of keyboard keyswitch design on hand pain. *Journal of Occupational and Environmental Medicine*, 41(2), 111-119.
- Rempel, D. M., Harrison, R. J., & Barnhart, S. (1992). Work-related cumulative trauma disorders of the upper extremity. *Jama-Journal of the American Medical Association*, 267(6), 838-842.
- Richter, J. M., Slijper, H. P., Over, E. A. B., & Frens, M. A. (2008). Computer work duration and its dependence on the used pause definition. *Applied Ergonomics*, 39, 772-778.
- Rose, M. J. (1991). Keyboard operating posture and actuation force - implications for muscle over-use. *Applied Ergonomics*, 22(3), 198-203.
- Samani, A., Holtermann, A., Sogaard, K., & Madeleine, P. (2010). Active biofeedback changes the spatial distribution of upper trapezius muscle activity during computer work. *European Journal of Applied Physiology*, 110(2), 415-423. doi: 10.1007/s00421-010-1515-6
- Sandow, A. (1952). Excitation-Contraction coupling in muscular response. *Yale Journal of Biology and Medicine*, 25(3), 176-&.
- Shi, J., Zheng, Y. P., Chen, X., & Huang, Q. H. (2007). Assessment of muscle fatigue using sonomyography: Muscle thickness change detected from ultrasound images. *Medical Engineering & Physics*, 29(4), 472-479. doi: 10.1016/j.medengphy.2006.07.004
- Silverthorn, D. U. (2007). *Human physiology : an integrated approach*. San Francisco: Pearson/Benjamin Cummings.
- Stephens, J. A., & Taylor, A. (1972). Fatigue of maintained voluntary muscle-contraction in man. *Journal of Physiology-London*, 220(1), 1-&.
- Sweeney, H. L., & Stull, J. T. (1990). Alteration of cross-bridge kinetics by myosin light phosphorylation in rabbit skeletal-muscle - implications for regulation of actin myosin interaction. *Proceedings of the National Academy of Sciences of the United States of America*, 87(1), 414-418.
- Takala, E. P. (2002). Static muscular load, an increasing hazard in modern information technology. *Scandinavian Journal of Work Environment & Health*, 28(4), 211-213.
- Tayyari, F., & Smith, J. L. (1997). *Occupational ergonomics : principles and applications*. London: Chapman & Hall.
- Valencia, F. (1986). Local muscle fatigue. A precursor to RSI? *The Medical journal of Australia*, 145(7), 327-330.
- van den Heuvel, S. G., de Looze, M. P., Hildebrandt, V. H., & The, K. H. (2003). Effects of software programs stimulating regular breaks and exercises on work-related neck and upper-limb disorders. *Scandinavian Journal of Work Environment & Health*, 29(2), 106-116.
- Van Eerd, D., Hogg-Johnson, S., Mazumder, A., Cole, D., Wells, R., & Moore, A. (2009). Task exposures in an office environment: a comparison of methods. *Ergonomics*, 52(10), 1248-1258. doi: 10.1080/00140130903023683
- Vandervoort, A. A., Quinlan, J., & McComas, A. J. (1983). Twitch potentiation after voluntary contraction. *Experimental Neurology*, 81(1), 141-152.
- Waersted, M., Hanvold, T. N., & Veiersted, K. B. (2010). Computer work and musculoskeletal disorders of the neck and upper extremity: A systematic review. *Bmc Musculoskeletal Disorders*, 11. doi: 10.1186/1471-2474-11-79

- Wahlstrom, J. (2005). Ergonomics, musculoskeletal disorders and computer work. *Occupational Medicine-Oxford*, 55(3), 168-176. doi: 10.1093/occmed/kqi083
- Westerblad, H., Bruton, J. D., Allen, D. G., & Lannergren, J. (2000). Functional significance of Ca^{2+} in long-lasting fatigue of skeletal muscle. *European Journal of Applied Physiology*, 83, 166-174.
- Westerblad, H., Bruton, J. D., Allen, D. G., & Lannergren, J. (2000). Functional significance of Ca^{2+} in long-lasting fatigue of skeletal muscle. *European Journal of Applied Physiology*, 83(2-3), 166-174.
- Wu, J. Z., An, K. N., Cutlip, R. G., Krajnak, K., Welcome, D., & Dong, R. G. (2008). Analysis of musculoskeletal loading in an index finger during tapping. *Journal of Biomechanics*, 41(3), 668-676. doi: 10.1016/j.jbiomech.2007.09.025

Appendix A. Recruitment E-mail (Chapter 2 and 4)

RECRUITMENT E-MAIL

RE: Participating in a Assessing Muscle Fatigue Using Electrical Stimulation at the University of Washington

To all:

Currently, a study is being conducted at the University of Washington in the Department of Environmental and Occupational Health Sciences assessing muscle fatigue associated with computer use by using electrical stimulation. We would like to invite you to participate in the study. The study is expected to last about 1-2 hours on the orientation day and 8 hours for the following four days. If you do decide to participate, you will be compensated \$15/hr for your time.

During this study, we will attach surface electrodes to your forearm. On the orientation day, we will introduce you to the electrical stimulation methods and the overall protocols. On the control day, you will be asked to rest for the whole eight hours. On each day of the four experimental days, you will be asked to perform four 75-min specific tasks using a keyboard and mouse with three breaks: a 15-min morning and afternoon break, and 30-min lunch break, respectively. Between the tasks, electrical stimulation and questionnaires will be use to assess your muscle fatigue. The electrical stimulation may cause discomfort, similar to “pins and needles,” tingling, or a sharp feeling like bumping the funny bone on your elbow. During the testing sessions you may watch movies or read, but you must not engage in any physical activity using your testing hand (i.e. using the computer, playing video games, talking on a cell phone, etc.).

Taking part in this study is voluntary. If you are 21 - 38 years old, right-handed and free of upper extremity injury, you are eligible for participation. If you are interested in participating in the study, please contact us by phone or e-mail and include the following information:

1. Dominant hand: Right ____ Left ____ Ambidextrous ____
2. Age:
3. History of upper-extremity disorders? Yes ____ No ____

Contact information is provided below.

*Please note that we cannot guarantee the confidentiality of information sent by e-mail.

Thank You,
Jeong Ho (Jay) Kim

=====

Jeong Ho (Jay) Kim
University of Washington
Industrial and Systems Engineering
4225 Roosevelt Way NE, Suite 100; Seattle, WA 98105
E-mail: jhkim01@uw.edu
Phone: (206)-543-4544

=====

Appendix B. Recruitment E-mail (Chapter 3)

RECRUITMENT E-MAIL

RE: Participating in a Computer Keyboard Study at the University of Washington

To all:

Currently, a study is being conducted at the University of Washington in the Department of Environmental and Occupational Health Sciences determining whether computer keyboard characteristics are associated with people using more force than necessary while typing. We would like to give you the opportunity to participate in the study. We are looking for right-handed participants age 18-65 to participate in a study on computer mouse design. The study will take 2-3 hours. If you do decide to participate, you will be compensated with \$20 / hr for your time in the form of an Amazon.com gift card.

During this study, we will attach electrogoniometers and EMG electrodes to your right arm in order to measure your hand and wrist posture and the load on your muscles while performing typing tasks using several different computer keyboards. We will ask you to fill out questionnaires after using each keyboard.

If you are interested in participating in the study or have any questions, please contact me by phone or e-mail. Please be careful with information sent via e-mail because we cannot assure confidentiality of information e-mailed to us. Contact information is provided below.

Thank You,

Erin Stamper

=====
Erin Stamper University of Washington

Environmental and Occupational Health Sciences
4225 Roosevelt Way NE, Suite 100; Seattle, WA 98105
E-mail: estamper@uw.edu Phone: (206-543-4727

=====

**UNIVERSITY OF WASHINGTON
CONSENT FORM**

ASSESSING MUSCLE FATIGUE USING ELECTRICAL STIMULATION

Researchers:

Peter Johnson, PhD, Assistant Professor (206) 221-5240	Department of Environmental and Occupational Health Sciences
Charlotte Lewis, PhD, Post Doc (206) 218-4278	Department of Environmental and Occupational Health Sciences
Jeong Ho (Jay) Kim, MS, Research Assistant (206) 543-4544	Department of Industrial and Systems Engineering
Erin Stamper, MPH, CPH (206) 543-4727	Department of Environmental and Occupational Health Sciences

Researchers' statement

We are asking you to be in a research study. The purpose of this consent form is to give you the information you will need to help you decide whether to be in the study or not. Please read the form carefully. You may ask questions about the purpose of the research, what we would ask you to do, the possible risks and benefits, your rights as a volunteer, and anything else about the research or this form that is not clear. When we have answered all your questions, you can decide if you want to be in the study or not. This process is called "informed consent." We will give you a copy of this form for your records.

PURPOSE OF THE STUDY

We want to determine 1) whether keystroke duration systematically changes as the durational exposure to keyboard work increases and whether the temporal changes in keystroke durations parallel objective measures from the muscle, 2) whether mouse button-click duration systematically changes as the durational exposure to mouse work increases and whether the temporal changes in mouse button-click durations parallel objective measures from the muscle.

STUDY PROCEDURES

We are asking you to participate in experiments on five separate days. The first day, is an orientation day which will last two hours, and the other four days consist of a control day and exposure days which will require 8 hours of participation each day. We need you to participate in these experiments on five separate days and we should be able to complete all measurements from you in a time period spanning no more than two weeks.

Orientation Day

During the orientation day, which will last approximately two hours, you will be introduced to the experimental techniques and procedures. This includes a period of time where you will be introduced electrical stimulation procedures. In addition, during the orientation you're your anthropometry will

be measured including 1) hand-size 2) wrist size (width, breadth, circumference), 3) forearm length 4) arm length 5) shoulder breadth 6) elbow to elbow breadth, 7) height and 8) weight. In addition, your demographic data such as age, years of computer mouse and keyboard use, and average daily and weekly computer use at home and work will be collected. To control for potential confounding associated with body posture, the workstation (an adjustable height table, adjustable ergonomic chair and adjustable computer monitor) will be set-up to match your anthropometry. Finally, the stimulation intensity you can acceptably tolerate will be determined. We will gradually ramp up the stimulation intensity until we reach your self-selected levels of acceptable stimulation. After testing, we will use henna ink to place small “mole size” dots on your skin to note the location of the stimulation electrodes. This will allow us to use the same placement sites on each subsequent experimental day. These henna marks will disappear in 7 – 12 days.

Experimental Days

The other four experimental days consist of three exposure day will last 8 hours including a 6-hour working time and a 2-hour recovery time. There will be 15-minute morning and afternoon breaks and a 30-minute lunch break. Before, during and after exposure to the intensive tasks (including keyboard use, mouse use and the combination of the two input devices) subjects will: 1) receive 2 Hz electrical stimulation to the right middle finger FDS muscle and the force response of the muscle will be measured (ES), 2) perform a standardized pointing task with the mouse (OP), 3) perform a standardized typing task (TT), 4) perform a finger tapping task with the ring finger (FT), 5) self-report their muscle fatigue (peripheral fatigue - PF), and 6) self-report their boredom (central fatigue-CF).

You can use the time in between the test measurements to meet your personal needs, like using the bathroom eating or drinking. Otherwise, we will request that you sit in a comfortable chair during the breaks between test sessions. Between the testing session and on the control day you may watch movies or read, but you must not engage in any physical activity using your testing hand (i.e. using the computer, playing video games, talking on a cell phone, etc.).

RISKS, STRESS, OR DISCOMFORT

We do not expect you to experience any substantial discomfort during the testing. Electrical stimulation of the muscle may be uncomfortable, but the risks to you are minimal. The electrical stimulation will give a “pins and needles,” tingling, or in some instances, a sharp feeling in the area of the skin under the electrodes. Before the study starts, we will attempt to minimize discomfort using careful placement of the electrodes and making sure you are comfortable with the stimulation. The stimulation will be isolated to your arm, and if the skin under the electrodes becomes irritated, you should tell the experimenter. Some people may be allergic to the henna ink and/or adhesive on the products used to attach the electrodes. In addition, when the electrodes are removed, you may experience a pulling sensation over the skin similar to the sensation when a band-aid is removed. If at any time you become uncomfortable, let the experimenter know. We will attempt to resolve your discomfort. You can stop the testing session at any time for any reason. If we feel we cannot successfully collect data, we may stop the experiment and terminate measurements.

BENEFITS OF THE STUDY

You will not directly benefit from taking part in this study. We hope that the results of this study help us to understand how muscle fatigue develops in response to prolonged, low-level activities such as working at the computer.

OTHER INFORMATION

Taking part in this study is voluntary, you may refuse to participate or may withdraw from the study at any time without penalty or loss of benefits to which they are otherwise entitled. The cost to you is your time, which you will be reimbursed for, along with the mental and physical discomfort that may be associated with being a subject in this research study. As partial compensation for your time and inconvenience, we will pay you USD \$15 per hour. You will be paid for your total participation time; if your participation ends during the hour, your participation time will be rounded up to the nearest half-hour and you will be paid accordingly. We will ask you to sign a receipt when you are paid for the purpose of our accounting records.

We will keep the study information confidential. We will assign an identity code to the study information. We will keep a master list of codes and identifiers in a secured location, separate from the study information. We will keep the study information linked to your name for 1 year, and then we will destroy the link to your identity. If we publish the results of this study, we will not use your name.

Government or university staff sometimes reviews studies such as this one to make sure they are being done safely and legally. If a review of this study takes place, your records may be examined. The reviewers will protect your privacy. The study records will not be used to put you at legal risk of harm.

If you think you have an injury or illness related to this study, contact the study staff right away. The study staff will treat you or refer you for treatment. If treatment is needed, the UW will pay up to \$10,000 to treat injury or illness caused by the study. You will not lose your legal right to seek payment if you sign this form.

Printed name of study staff obtaining consent	Signature	Date
---	-----------	------

Subject's statement

This study has been explained to me. I volunteer to take part in this research. I have had a chance to ask questions. If I have questions later about the research, I can ask one of the researchers listed above. If I have questions about my rights as a research subject, I can call the Human Subjects Division at (206) 543-0098. [If relevant, add: I give permission to the researchers to use my medical records as described in this consent form.] I will receive a copy of this consent form.

Printed name of subject	Signature of subject	Date
-------------------------	----------------------	------

Copies to: Researcher
 Subject

Appendix D. Questionnaire for measuring peripheral fatigue (Chapter 4)

Borg Scale.vi Front Panel

File Edit View Project Operate Tools Window Help

18pt Application Font

Borg Fatigue/Discomfort Questionnaire

time string: 12:36 PM

date string: 3/20/2011

Subject Identifier: S20 Experiment Day: Experiment Day 3 Measurement: 3 Condition 2:

Mark and X on the line that accurately represents your level of fatigue.

1. How much fatigue does your **RIGHT middle finger** experience?

0 0.5 1 2 3 4 5 6 7 8 9 10

Not Fatigued Slightly Fatigued Moderately Fatigued Fatigued Very Fatigued Severely Fatigued

2. How much fatigue does your **RIGHT wrist** experience?

0 0.5 1 2 3 4 5 6 7 8 9 10

Not Fatigued Slightly Fatigued Moderately Fatigued Fatigued Very Fatigued Severely Fatigued

3. How much fatigue does your **RIGHT elbow** experience?

0 0.5 1 2 3 4 5 6 7 8 9 10

Not Fatigued Slightly Fatigued Moderately Fatigued Fatigued Very Fatigued Severely Fatigued

4. How much fatigue does your **RIGHT shoulder** experience?

0 0.5 1 2 3 4 5 6 7 8 9 10

Not Fatigued Slightly Fatigued Moderately Fatigued Fatigued Very Fatigued Severely Fatigued

5. How much fatigue does your **neck** experience?

0 0.5 1 2 3 4 5 6 7 8 9 10

Not Fatigued Slightly Fatigued Moderately Fatigued Fatigued Very Fatigued Severely Fatigued

SAVE

Appendix E. Questionnaire for measuring central fatigue (Chapter 4)

VAS central fatigue.vi Front Panel

File Edit View Project Operate Tools Window Help

18pt Application Font

VAS Mental Fatigue Questionnaire

time string: 12:48 PM

Subject Identifier: S20 Experiment Day: Experiment Day 3 Measurement: 3 Condition 2: date string: 3/20/2011

DIRECTIONS: You are asked to choose a number on each of the following lines to indicate how you are feeling **RIGHT NOW**.

- tired
Not at all 0 1 2 3 4 5 6 7 8 9 10 Extremely
- sleepy
Not at all 0 1 2 3 4 5 6 7 8 9 10 Extremely
- drowsy
Not at all 0 1 2 3 4 5 6 7 8 9 10 Extremely
- fatigued
Not at all 0 1 2 3 4 5 6 7 8 9 10 Extremely
- worn out
Not at all 0 1 2 3 4 5 6 7 8 9 10 Extremely
- bushed
Not at all 0 1 2 3 4 5 6 7 8 9 10 Extremely
- exhausted
Not at all 0 1 2 3 4 5 6 7 8 9 10 Extremely
- Keeping my eyes open is
no effort at all 0 1 2 3 4 5 6 7 8 9 10 a tremendous chore
- Moving my body is
no effort at all 0 1 2 3 4 5 6 7 8 9 10 a tremendous chore
- Concentrating is
no effort at all 0 1 2 3 4 5 6 7 8 9 10 a tremendous chore
- Carrying on a conversation is
no effort at all 0 1 2 3 4 5 6 7 8 9 10 a tremendous chore
- I have absolutely
no desire to close my eyes 0 1 2 3 4 5 6 7 8 9 10 a tremendous desire to close my eyes
- I have absolutely
no desire to lie down 0 1 2 3 4 5 6 7 8 9 10 a tremendous desire to lie down

SAVE

CURROCULUM VITAE

JEONG HO (JAY) KIM

EDUCATION

- 2008 - 2012 Ph.D in Industrial and Systems Engineering**
University of Washington – Seattle
Thesis Advisor: Peter W Johnson, Ph.D
Thesis: Non-invasive real-time assessment of muscle fatigue during computer use:
using mouse button click and keystroke duration.
- 2005 - 2007 M.S. in Industrial and Systems Engineering**
University of Wisconsin - Madison
Focused on Quality Engineering
- 1995 - 2003 B.S. in Industrial and Systems Engineering**
Dankook University, South Korea
Minor in Economics

PROFESSIONAL EXPERIENCE

- 2009 - present ERGONOMICS LAB at the University of Washington – Seattle, WA**
Predoctoral Research Associate, project coordinator
• Design studies and develop data acquisition methods
• Lead externally-funded projects
- 2003 - 2004 MOLEX KOREA, Quality Management Division – South Korea**
Quality Engineer
• Designed and developed various statistical quality control methods
- 1997 - 1999 REPUBLIC OF KOREA ARMY – South Korea**
Headquarter Sergeant
• Served in the department of transportation

HONORS AND AWARDS

- 2012** GPSS Travel Grant, University of Washington
- 2011** IEA KU Smith Award finalist (**best student paper**), International Ergonomics Association
- 2011** Community of Innovators Awards nominee (**best student researcher**), College of Engineering
- 2011** Graduate student travel award, University of Washington
- 2009 - present** Predoctoral Research Assistantship, University of Washington
- 2009** Alpha Pi Mu, the National Industrial Engineering Honor Society
- 2008 - 2009** Predoctoral Teaching Assistantship, University of Washington
- 2008** Clairmont L. Egtvedt Fellowship, University of Washington
- 2003** Employee of the year, Molex Korea
- 2000 – 2002** Scholarship with Academic distinction, Dankook University

TEACHING EXPERIENCE

- 2008 - 2009** *Teaching Assistant, University of Washington - Seattle*
INDE 315: Probability and Statistics for Engineers, Fall 2008 – Winter 2009
INDE 351: Human Factors in Engineering Design, Spring 2009
ENVH 566: Introduction to Ergonomics, Winter 2012

BIBLIOGRAPHY

Peer Reviewed Papers

1. **Kim, JH**, Johnson PW. (Accepted) Viability of Using Digital Signals from the keyboard to Capture Typing Force Exposures. *Ergonomics*

Peer Reviewed Papers in preparation

1. **Kim JH**, Johnson PW. Physiological variations between keyboard and mouse use. Target Journal - *European Journal of Applied Physiology*.
2. **Kim JH**, Johnson PW. Validation of a Software Program for Measuring Fatigue-Related Changes in Mouse Button Click and Keystroke Durations. Target Journal – *International Journal of Industrial Ergonomics*.
3. **Kim JH**, Aulck L, Johnson PW. Are There Any Differences in Physical Exposures and Typing Performance between Conventional and Virtual Keyboards? Target Journal – *Human Factors*
4. **Kim JH**, Aulck L, Thamsuwan O, Johnson PW, The Effects of Key Sizes of Touch Screen Virtual Keyboard on Productivity, Usability, and Typing Forces. Target Journal – *Ergonomics*
5. **Kim JH**, Aulck L, Bartha M, Harper CA, Johnson PW. Differences in Force Exposures, Muscle Activity, Discomfort, and Typing Performance between a Virtual, Notebook, and Desktop Keyboard. Target Journal – *JEMGK*

Other Scholarly Peer-reviewed Publications/Presentations

1. **Kim JH**, Johnson PW. (2011) Validation of software-based measures of keystroke durations with external USB-based logger. 61st Annual Industrial Engineering Research Conference, Reno, NV.
2. **Kim JH**, Johnson PW. (2011) Validation of a Software Program for Measuring Fatigue-Related Changes in Keystroke Durations. 33rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Boston, MA.
3. **Kim JH**, Johnson PW. (2012) Can Digital Signals from the Keyboard Capture Force Exposures during Typing? *Work* No.4 2588-2590.
4. **Kim JH**, Johnson PW. (2012) Can Digital Signals from the Keyboard Capture Force Exposures during Typing? 18th World Congress on Ergonomics, Recife, Brazil.
5. **Kim JH**, Johnson PW. (accepted) Validation of a Software Program for Measuring Fatigue-Related Changes in Keystroke Durations. Annual US-Korea Conference on Science and Engineering 2011, Park City, UT.
6. **Kim JH**, Aulck L, Johnson PW. (accepted) Typing Force and Performance Variability between Conventional and Virtual Keyboards. 62nd Annual Industrial Engineering Research Conference, Orlando, FL.
7. **Kim JH**, Aulck L, Bartha M, Harper CA, Johnson PW. (submitted) Are there Differences in Force Exposures and Typing Productivity between Touchscreen and Conventional Keyboard? Human Factors and Ergonomics Society 56th Annual Meeting, Boston, MA.

8. **Kim JH**, Aulck L, Bartha M, Harper CA, Johnson PW. (submitted) Are there Differences in Muscle Activity, Subjective Discomfort, and Typing Performance between Virtual and Conventional Keyboards? 34th Annual International Conference of the Engineering in Medicine and Biology Society, San Diego, CA.

Other Non-referred Publications/Presentations

1. **Kim JH**, Johnson PW. (2011) Validation of UW/Harvard Computer Interaction Monitoring Software for Measuring Fatigue-Related Changes in Keystroke Durations. 23rd Annual Occupational, Environmental, and Public Health Conference, Blain, WA.
2. **Kim JH**, Johnson PW. (2011) Can Digital Signals from the Keyboard Capture Force Exposures during Typing? Northwest Biomechanics Symposium 2011, Vancouver, BC, Canada
3. **Kim JH**, Johnson PW. (2011) Computer Input Devices as a surrogate exposure assessment tool. Korean-American Engineers and Scientists Association Northwest Regional Conference 2011, San Jose, CA.
4. **Kim JH** (2011) Non-invasive Real-time Assessment of Muscle Fatigue during Computer Use, Industrial and Systems Engineering Graduate Seminar: IND E 593, University of Washington, Seattle, WA
5. **Kim JH** (2012) Non-invasive Real-time Assessment of Muscle Fatigue during Computer Use, 2012 Spring Biomechanics Seminar Series: ME 598, Department of Mechanical Engineering, University of Washington, Seattle, WA

FUNDED PROJECTS

2009 - 2011	Evaluation of computer mouse and keyboard as exposure assessment tools. Peter W. Johnson, PhD. (PI), NIOSH (R21). \$275,000, Research Assistant, 50% effort
2011 - present	Ergonomic and human factors analysis of virtual keyboards. Peter W. Johnson, PhD. (PI), Hewlett Packard. Study Coordinator, 25% effort.
2011 - present	Ergonomic and human factors analysis of low travel keyboards. Peter W. Johnson, PhD. (PI), Hewlett Packard. Study Coordinator, 25% effort.

SERVICE

Reviewer, Journal, *Applied Ergonomics*

Reviewer, Journal, *Human Factors*

Reviewer, Industrial Ergonomics Technical group, 56th Human Factors and Ergonomics Society Annual Meeting (2012)

Chair, Ergonomics Track, 62nd IIE Annual Applied Solution Conference (2012)

Officer, Alpha Pi Mu, National Industrial Engineering Honor Society, (2011-2012)

AFFILIATIONS

Institute of Industrial Engineers

Human Factors and Ergonomic Society

Korean-American Scientists and Engineers Association

Alpha Pi Mu, the National Industrial Engineering Honor Society

SKILLS AND QUALIFICATION

Strong background on statistics: Multivariate, Bayesian, Bootstrapping, Simulation, etc.

Programming language: JAVA, LabVIEW, Matlab

Statistic Software: R, JMP, SPSS, Minitab, STATA

Fluent in English and Korean

Work well in team as well as independently