Effects of Time Pressure and Mental Workload on Physiological Risk Factors for Upper Extremity Musculoskeletal Disorders While Typing

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Abstract

Work-related musculoskeletal disorders (WMSDs) are a major source of lost productivity and revenue in the workplace and disability in workers. There is strong evidence for a relationship between physical risk factors, such as repetitive motions and excessive force, and the development of WMSDs; yet there are unexplained discrepancies in determining which workers are more at risk. Researchers hypothesize that non-physical factors in the workplace, or psychosocial factors, may contribute to the development of WMSDs. The following study examined the effects of two psychosocial factors, mental workload and time pressure, on perceived workload and physiological reactions of the lower arm and wrist during typing activity by measuring muscle activation patterns, wrist posture and movement, key strike forces, and subjective assessments of overall workload. The results indicate that increases in time pressure lead to increases in lower arm muscle activation, key strike forces, and wrist deviations. Key strike forces may increase with higher mental workload levels, but other effects of mental workload were not clear. Perceived overall workload (time load, mental effort load, and stress load) increased with mental workload and time pressure, and typing performance decreased. The evidence from this study suggests that these psychosocial factors (mental workload and time pressure) mediate physical risk factors to increase risk for WMSD development in the upper extremities. The results illustrate the need for those designing jobs and work tasks to consider both physical and psychosocial aspects of the working environment to prevent injuries in employees.

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Introduction

Background

Work-related musculoskeletal disorders (WMSDs) continue to be a major source of lost productivity and revenue in the workplace. In 2001, nearly 34% of all nonfatal occupational injuries and illnesses that resulted in days away from work were attributable to musculoskeletal disorders (Bureau of Labor Statistics (BLS), 2003). A total of 81,398, or over 5%, of all reported injuries and illnesses were disorders of the upper extremities (BLS, 2003). Furthermore, 11,427 cases occurred in jobs involving typing or key entry, requiring recovery periods with a median of 16 days per year away from work (BLS, 2003). Upper-extremity WMSDs are common among workers that use visual display terminals (VDTs) and keyboards extensively, such as employees in the telecommunications and newspaper industries (Fine, 1996). However, the causes of upper-extremity WMSDs, in particular those of the hand and wrist, are not well understood. Researchers have divided potential risk factors for WMSDs into physical, psychosocial, and individual factors. While physical risk factors, such as repetitive motions and forceful exertions, are generally accepted as contributing to upper-extremity WMSDs, the evidence of association of psychosocial and individual factors is currently much weaker.

The Panel on Musculoskeletal Disorders and the Workplace (National Research Council and the Institute of Medicine, 2001) has identified the influence of psychological stress and psychosocial factors on musculoskeletal response as an area that needs more research. The U.S. Department of Health and Human Services has also identified this topic as a priority research area (Department of Health and Human Services, 2001). Epidemiological studies and literature reviews have found associations between the development of WMSDs and several physical, psychosocial, and individual factors (Aptel, Aublet-Cuvelier, & Cnockaert, 2002; Bongers, de Winter, Kompier, & Hildebrandt, 1993; Buckle, 1997; Buckle & Devereux, 2002; Malchaire, Cock, & Vergracht, 2001). Currently, psychosocial factors such as time pressure, perceived high workload, and low social support are associated in some studies with an increased risk for WMSD development, but very few experimental studies have examined the contribution of these factors to WMSDs of the hand and wrist.

Statement of the Problem

Psychosocial factors such as time pressure, lack of social support from colleagues and management, low decision latitude, job satisfaction, and high perceived workload have been associated with the development of upper limb WMSDs (Bongers et al., 1993; Buckle, 1997; Leclerc, Landra, Chastang, Niedhammer, & Roquilaure, 2001). Studies have examined the effects of time pressure and mental workload on upper-body muscles. McLean and Urquhart (2002) studied the effects of psychosocial stress on the trapezius and levator scapulae muscles and found that adding time pressures to a typing task decreased the number of rests in muscle activity (EMG gaps) and that adding distraction stress increased the level of muscle activation. Leyman, Mirka, Kaber, and Sommerich (2001) studied changes in muscle activity of the cervical erector spinae and trapezius muscles that resulted from adding mental tasks to a typing task. As the level of mental task difficulty increased, the level of muscle activation also increased. The results of these two studies are consistent with epidemiological findings that show that time pressure and high workload, along with other physical, individual, and psycho-organizational factors, are associated with an increased risk for developing WMSDs of the upper extremity (Bongers et al., 1993).

Much of the research on psychological influences on musculoskeletal response, however, has concentrated on the lower back, shoulders, or neck. Little research has been conducted on the effects of psychosocial factors on the lower arm, hand, and wrist (Malchaire et al., 2001). The high prevalence of WMSDs of the hand and wrist warrants the need for research into psychosocial factors as either causes or mediating factors in the development of these disorders.

Objective of the Study

The objective of this study was to examine the effects of mental workload and time pressure on the musculoskeletal response of the lower arm and wrist during a typing task. Mental workload was manipulated by adding mathematical tasks during data entry tasks, and time pressure was simulated by requiring participants to type a certain amount of text within specified time limits. Changes in muscle activation, wrist posture, and key strike force were measured to assess changes in musculoskeletal response. Three visual-analog scales developed from the subjective workload assessment technique (SWAT) were marked immediately following the completion of each experimental trial to subjectively assess the time load, mental pressure load, and stress load participants experienced during each trial. Individual differences in gender, locus of control, and perceived stress (which may be confounding factors) were considered in the analysis when determining the effect of increasing levels of time pressure and mental workload on lower arm muscle activation, wrist posture, and key strike forces.

Several hypotheses were tested:

1. The highest stress levels that participants experience will result from trials that combine both high time pressure and high mental workload. Based on observations from a pilot study, additional mental workload will generate more feelings of stress than time pressure.
2. Typing performance will decrease as levels of time pressure and mental workload increase. This will be reflected by a decrease in net typing speed and an increase in the number of errors committed.
3. Increased levels of time pressure and mental workload will lead to an increase in lower arm muscle activation and a decrease in the number of pauses in muscle activity. Previous studies have shown that increases in time pressure and mental workload increase muscle activation in the shoulder and neck region (Leyman et al., 2001; McLean & Urquhart, 2002) and in finger flexor and extensor muscles (Gerard, Armstrong, Martin, & Rempel, 2002).
4. Increases in both time pressure and mental workload will result in increased average key strike forces. Studies have shown that higher speeds of typing lead to higher key strike forces (Gerard et al., 2002). Being asked to type at higher speeds may be a potentially stressful situation due to time pressure. Because this stressor leads to higher key strike forces, it is logical that other stressors, such as increased mental workload, will also induce higher key strike forces.
5. The number of measurable wrist movements will be affected by changes in time pressure and mental workload level. As time pressure increases, typing speed will increase, and therefore the number of measurable wrist movements will also increase. However, as mental workload increases, participants may become more tense and keep their wrists in a more static and awkward position. This will result in a decrease in the total number of measurable wrist movements. When compared to control trials, trials that combine time

pressure and additional mental workload may appear to have less difference in the number of wrist movements than trial conditions with only one of these added conditions.

6. The magnitude of average wrist posture will become more extreme (more deviated from neutral position) in both the flexion/extension plane and the radial/ulnar plane as mental workload and time pressure increase.
7. Individual traits of perceived stress and locus of control, as measured by the perceived stress scale and locus of control questionnaire, will affect muscle activity, key strike force, wrist movements and posture, and performance. Individuals with higher perceived stress levels and a higher internal locus of control may display more noticeable effects of time pressure and mental workload on physiological responses than those who are better able to cope with stressful situations or who have a more external locus of control.
8. No gender differences are expected in this study. Although gender may play a role in the development of hand and wrist WMSDs, this discrepancy is more likely caused by the traditional hand intensive and repetitive types of tasks performed by women and by the different responses of women in general to psycho-organizational factors. There is evidence that gender is not a significant factor in the susceptibility to developing WMSDs when men and women perform identical tasks (Malchaire et al., 2001).

Scope and Limitations of the Study

Although many physical, individual, and psychosocial factors are thought to contribute to the development of WMSDs, the current study will focus only on the effects of time pressure and mental workload on musculoskeletal response during a typing task. Both of these factors are thought to increase stress levels, where stress is defined as a phenomenon that occurs when people feel unable to manage the demands placed on them (Bongers et al., 1993). Mental workload is defined by Hart and Staveland (1988, p.144) as a "construct that represents the cost incurred by a human operator to achieve a particular level of performance." In this study it will be adjusted by the number and difficulty of concurrent activities being attempted by participants. Subjective workload, which is defined by Reid and Nygren (1988, p. 187) as a person's "direct estimate or comparison judgment of the workload experienced at a given moment", will be assessed after each experimental trial. Muscle activity of the lower arm, wrist posture, and key strike forces will be the only physical outcomes measured although other studies have proposed examining other physiological responses, such as hormone levels and heart rate (McLean &

Urquhart, 2002; Viikari-Juntura & Riihimaki, 1999). Gender and typing proficiency will be controlled in recruiting participants for the study, and locus of control and perceived stress ratings will be the only other individual factors studied. Individual factors such as age and ethnicity will be recorded but not considered in the analysis. The nature of the task under investigation will be limited to typing on a conventional keyboard only. The use of a mouse or other input devices will not be considered because additional activities would introduce more variability to dependent measures of muscle activity and wrist posture.

Literature Review

Work-Related Musculoskeletal Disorders and Risk Factors

Work-related musculoskeletal disorders (WMSDs) are inflammatory and degenerative disorders that cause pain and functional impairment to the soft tissues of the body (tendons, muscles, joints, nerves, and blood vessels). The World Health Organization further defines WMSDs as multifactorial phenomena that are significantly associated with physical, psychosocial, and sociological factors present in the workplace (as cited in Aptel et al., 2002). WMSDs of the upper extremity include, but are not limited to, epicondylitis, tendonitis, carpal tunnel syndrome (CTS), and Raynaud's phenomenon (Aptel et al., 2002) Categories of risk factors, which are generally divided into physical, psychosocial, and individual factors, have been identified as having an association with the development of WMSDs. Much of the research that has been conducted on WMSDs has focused on occupational or physical risk factors primarily to determine work-relatedness. However, psychosocial risk factors are hypothesized to play either a direct or mediating role in the development of work-related disorders, and have received more attention recently.

Psychosocial Factors as Risk Factors for WMSD Development

Psychosocial factors can be defined as "perceptions or beliefs held by workers regarding the way the work is organized" (Buckle & Devereux, 2002). Sauter and Swanson (1996) use a more broad definition stating that psychosocial factors are any elements, work or individual, which contribute to the stress process. In general, psychosocial or psycho-organizational factors cover non-physical areas of work, such as time pressure, perceived workload, social support from both colleagues and management, and level of control. Psychosocial factors can have a positive or negative effect on the development of WMSDs. For instance, high levels of support from supervisors may decrease risk for WMSDs whereas low level of control over work organization may increase risk. The link between psychosocial factors and the development of WMSDs is less clear than that of biomechanical risk factors. Psychosocial factors may influence biomechanical loads and stress reactions, which can lead to the development of WMSDs (Buckle & Devereux, 2002).

Literature Review

The broadness of the term “psychosocial factors” and the difficulty in measuring psychosocial factors objectively are obstacles that have made studying the role of these factors in the development of WMSDs difficult (Sauter & Swanson, 1996). In the past, surveys have been the most common method of obtaining information on psychosocial factors at work. In their review of epidemiological literature, Bongers et al. (1993) found that monotonous work, time pressure, high perceived workload, high job demands, low control, poor social support, psychological and emotional problems, and stress symptoms are all associated with WMSD development. Buckle (1997) also found that low decision latitude and lack of social support are contributing factors.

The position taken for the current research on the contribution of psychosocial factors in the process of hand/wrist WMSD development will follow the suggestions of Bongers et al. (1993). They hypothesize that psychosocial factors directly influence mechanical loads by changing postures, motions, and forces. For example, time pressure may lead to faster motions in completing a task. The authors also suggest that the influence of psychosocial factors contribute to stress, which may increase risk for WMSD development.

Stress has been defined as occurring when people feel unable to manage the demands placed on them. Stress may mediate symptoms of WMSDs by enhancing perceptions of symptoms and by reducing the capacity to cope with the symptoms (Bongers et al., 1993). Physiologically, stress causes an increase in muscle tone, which can lead to higher loads on muscles and tendons. It also decreases microcirculation, which can cause fatigue, myalgia, and slower healing. Stress may lead to entrapment syndromes due to edema (Aptel et al., 2002). Finally, stress causes changes in immune system responses such as the release of interleukins, a proinflammatory substance which helps regulate inflammatory and immune responses (Aptel et al., 2002, "Definition for: Interleukins", 1997). Although stress is considered a result of psychosocial factors, there is little evidence for biological mediation between psychosocial factors and WMSD development (Sauter & Swanson, 1996).

A proposed model of psychosocial factors in the development of WMSDs is illustrated in Figure 1, based on models developed by Sauter and Swanson (1996) and Melin and Lundberg (1997). In the model, physical stressors cause physiological stress responses, such as increased muscle tension, and lead directly to physical WMSD risk factors. Psychosocial stressors influence physical WMSD risk factors indirectly by contributing to physical stressors and stress responses, and/or lead directly to WMSDs by inducing physiological stress responses. Individual factors such as medical conditions or gender may mediate the effects of physical and psychosocial stressors as they contribute to stress responses. The physical WMSD risk factors lead to work-related disorders over time.

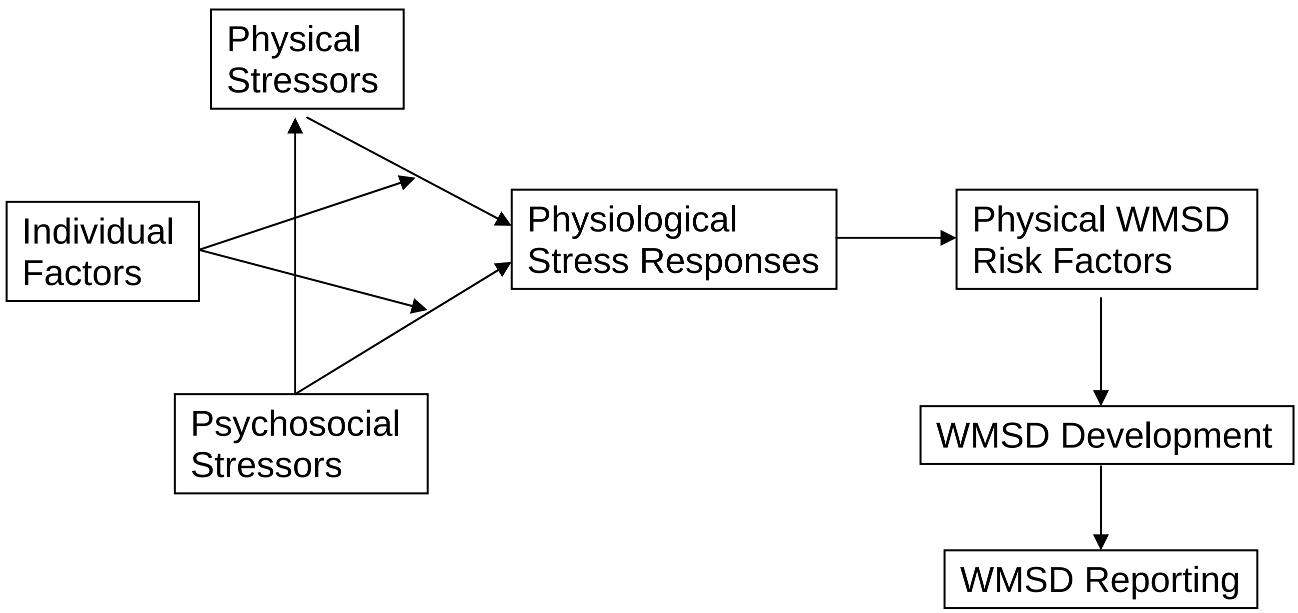

Figure 1. Psychosocial factors model

The Influence of Psychosocial Factors in the Development of Hand/Wrist WMSDs

Little is known about the contribution of psychological factors to the development of upper limb disorders, and the interrelationship of physical and psychosocial factors is rarely examined. Additionally, there are few studies available that have examined the influence of psychosocial factors on hand and wrist WMSDs specifically. Recent epidemiological studies have associated a few factors, such as time pressure and low job control, with upper limb WMSDs (Buckle, 1997). A study of newspaper employees found that more hours of VDT (visual display terminal) use per day and less decision latitude were significant risk factors for the development of upper-extremity WMSDs and that lower levels of co-worker support were associated with WMSDs (Faucett & Rempel, 1994). A longitudinal epidemiological study was recently completed which examined the possible associations of risk factors, including several psychosocial factors, to the development of wrist tendonitis, carpal tunnel syndrome, and lateral epicondylitis (Leclerc et al., 2001). Biomechanical characteristics of the jobs were associated with all three disorders. Other predictive factors for wrist tendonitis included lack of social support, somatic problems, body-mass index (BMI) increase, and age. Interestingly, older workers were less likely to develop wrist tendonitis, perhaps due to a healthy worker survivor effect. Carpal tunnel syndrome was associated with an increase in BMI and job satisfaction for women. Older subjects were more likely to develop lateral epicondylitis, and the presence of depressive symptoms also displayed a relationship with this disorder.

Tasks performed in office work, such as data entry and word processing, generally do not have the same physical characteristics of other jobs at high risk for upper-limb WMSDs, such as in the meat packing industry (Fine, 1996). However, the high prevalence of upper-extremity WMSDs in office work indicates that some other individual and/or psychosocial factors contribute to the development of WMSDs. Therefore, a need exists to quantify the relationship between the physical characteristics of typing activities and the psychosocial factors that may be present in office environments.

Physical Characteristics of Typing Activities

Studies have been conducted previously that examine wrist posture, lower arm muscle activation, and key strike force during typing tasks. Typing is a highly repetitive activity (Gerard et al., 2002), and it often involves extreme postures of the wrist and forearm (Serina, Tal, & Rempel, 1999; Simoneau, Marklin, & Monroe, 1999). Since these characteristics are risk factors for the development of upper-extremity WMSDs, employees that use VDTs and keyboards extensively, such as those in the telecommunications and newspaper industries, often develop upper-extremity WMSDs (Fine, 1996).

Wrist Posture During Typing

Studies investigating wrist posture during typing tasks show that the wrists exhibit a significant amount of pronation, extension, and ulnar deviation. Studies reveal that the wrist is in anywhere from 17.0° to 23.4° of extension on average while typing on a conventional keyboard. Average ulnar deviation is also considerable, ranging from 10.1° to 18.6° (Serina et al., 1999; Simoneau et al., 1999). Forearm pronation may be anywhere from 62.2° for the left arm and 65.6° for the right arm (Simoneau et al., 1999) to 90.3° for the left arm and 83.2° for the right arm (Serina et al., 1999). There is conflicting evidence for measured differences between right and left hands, with Simoneau et al. (1999) showing significant differences in all three planes of motion between hands, while Serina et al. (1999) found no significant differences.

Muscle Activity During Typing

Faster typing speeds have been shown to lead to an increase in muscle activity (Gerard et al., 2002; McLean & Urquhart, 2002). One early study by Lundervold (1958) showed that muscle activation increased as typing speed increased (as cited in Sommerich, 1994). Gerard et al. (2002) found that finger flexor and extensor muscles showed higher activation levels as typing speed increased. McLean and Urquhart (2002) found a decrease in muscle inactivity (EMG gaps) of the trapezius and levator scapulae muscles when time pressure was added to a typing task.

Key Strike Force During Typing

Previous research indicates that typists put themselves at risk by exerting unnecessarily high forces when activating keys. Average key activation force can range from 0.2 N to 0.9 N (Rose, 1991), but typists exert up to 4.6 times more force as measured by load cells embedded in keyboards than necessary to activate keys (Armstrong, Foulke, Martin, Gerson, & Rempel, 1994; Feuerstein, Armstrong, & Hickey, 1994). Additionally, reaction forces measured at the keyboard with load cells are much lower than the actual muscular forces exerted for key activation (Martin et al., 1996). Martin et al. (1996) found average key strike forces of 0.86 N from reaction forces on the keyboard but estimated the actual muscle force used to be 5.93 N based on EMG readings.

In addition to using higher forces while keyboarding, typing force has been shown to increase with typing speed (Gerard et al., 2002). Forceful exertions are considered a risk factor for WMSDs, but the exact mechanism that leads to the development of specific disorders is unclear. Sommerich (1994) found that key strike force did not affect carpal tunnel pressure.

Effect of Psychosocial Factors During Typing

There are a few studies that investigate the effects of stress in the form of time pressure and mental load on physiological parameters while typing. However, previous studies have concentrated on the effects of stress on shoulder and neck muscles, and none have examined effects on lower arm muscles, particularly those muscles used during typing. Bongers et al. (1993) states that an increase in perceived stress can lead to an increase in muscle tension. This is supported by a study done by McLean and Urquhart (2002) that showed an increase in EMG amplitude of shoulder muscles (trapezius and levator scapulae) when distractions were added to a typing task. A study by Leyman et al. (2001) found that adding mental tasks to a typing task, which would presumably increase perceived stress, increased muscle activity in the cervicobrachial region. Other effects of mental workload and time pressure include decreased typing speed with the addition of mental tasks (Leyman et al., 2001) and elevated carpal tunnel pressure with increases in typing speed (Sommerich, 1994).

Summary

Physical, psychosocial, and individual factors are all thought to contribute to the development of upper-extremity WMSDs. Most research has concentrated on determining work-relatedness of physical factors for WMSD risk, but there is evidence that psychosocial factors play either a direct (moderating) or mediating role in the development of WMSDs. Typing is one occupational activity associated with high levels of hand and wrist WMSDs, though there is limited research on how psychosocial factors might contribute to the development of these disorders. Previous studies have demonstrated that time pressure and additional mental tasks increase muscle activation of the shoulder region and the finger flexor and extensor muscles during typing tasks. Research also shows that key strike force increases with time pressure during typing. However, deficiencies exist in the research on how time pressure and additional mental workload affect wrist posture and muscle activity of the lower arm muscles that are used in typing, and on how additional mental workload affects key strike forces. The current research sought to bridge the gap between the effects of psychosocial factors on typing habits and physical outcomes that are established risk factors for the development of hand and wrist WMSDs.

Time pressure and mental workload may affect physical outcomes directly by forcing changes in typing habits to meet performance demands and indirectly by increasing stress levels, which has physiological effects on the body. Using the model described previously (Figure 1), it is hypothesized that psychosocial factors of mental workload and time pressure will act as a mediating factor by increasing the magnitude of physical stressors of forceful exertions (key strike force), muscle activation, and awkward postures of the wrist. Mental workload and time pressure may also directly increase physiological stress responses by increasing perceived workload and stress levels. Individual factors of gender, perceived stress (PSS) and locus of control (LOC) are hypothesized to affect perceived stress and workload (Figure 2).

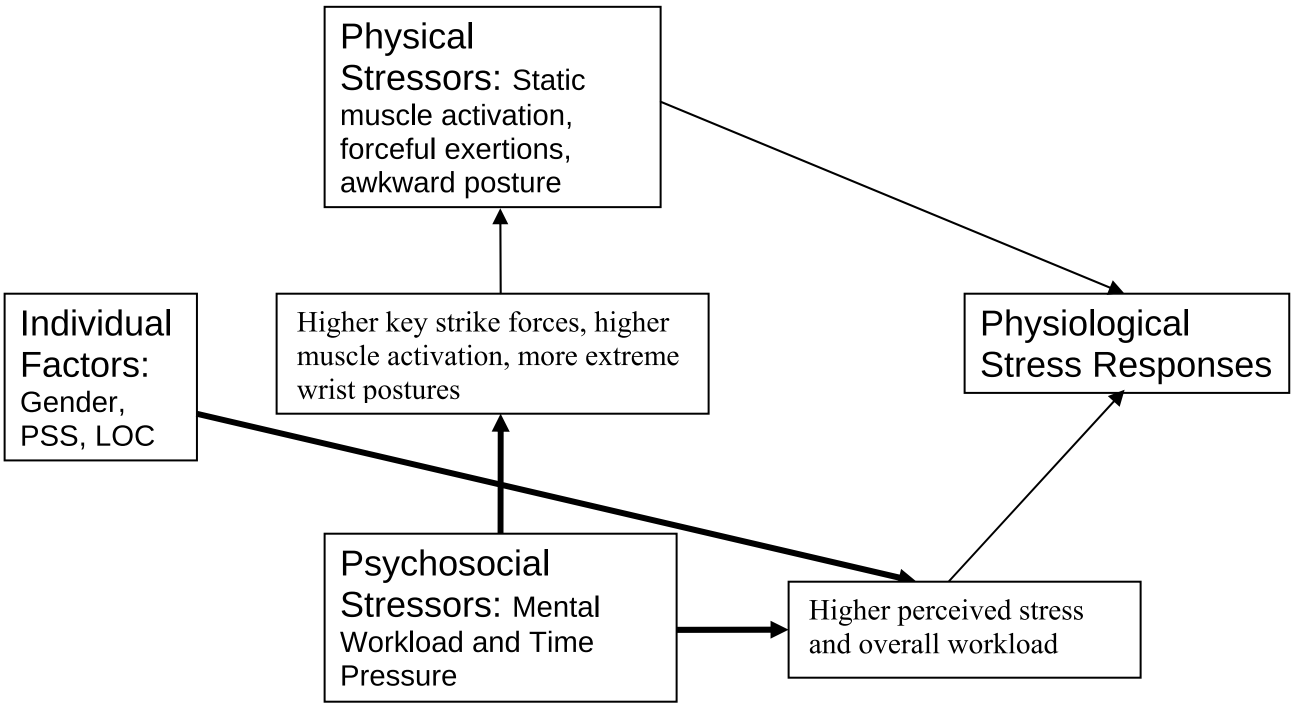

Figure 2. Hypothesized effects of mental workload and time pressure in the psychosocial factors model. (Bold arrows indicate relationships examined in the current study.)

Methods

Design of Experiment

A 3 x 3 full factorial repeated measures study was performed to study the effects of mental workload and time pressure on several dependent variables. Mental workload was manipulated by requiring participants to complete concurrent tasks (math problems) while time pressure was controlled by requiring participants to complete a certain amount of work within a specified time period. Mental workload and time pressure have three levels denoted as control, low, and high. Both factors were within-subjects variables; therefore each participant completed nine trials. A balanced Latin square was used to determine trial order (Table 1 and Table 2).

Table 1. Trial level combinations.

Trial Code	Mental workload level	Time pressure level
1	Control	Control
2	Control	Low
3	Control	High
4	Low	Control
5	Low	Low
6	Low	High
7	High	Control
8	High	Low
9	High	High

Table 2. Latin square design for trial order assignment. Numbers indicate the trial code given in Table 1. The reverse trial order was used for participants 10 through 18.

	Participant Number								
Trial Order	P 1, 10	P 2, 11	P 3, 12	P 4, 13	P 5, 14	P 6, 15	P 7, 16	P 8, 17	P 9, 18
1	1	2	3	4	5	6	7	8	9
2	2	3	4	5	6	7	8	9	1
3	9	1	2	3	4	5	6	7	8
4	3	4	5	6	7	8	9	1	2
5	8	9	1	2	3	4	5	6	7
6	4	5	6	7	8	9	1	2	3
7	7	8	9	1	2	3	4	5	6
8	5	6	7	8	9	1	2	3	4
9	6	7	8	9	1	2	3	4	5

Independent Variables

Mental workload and time pressure were manipulated by imposing a concurrent task (math problems) and by imposing a time pressure condition of typing at an elevated speed. Both variables included three levels: control, low, and high. The control level of mental workload was the absence of any math tasks. The low-level mental workload condition consisted of answering single-digit addition questions excluding the digits 0 and 1. The high level required participants to answer single-digit multiplication questions excluding the digits 0, 1, and 2. These digits were excluded because they are simple compared to the rest of the digits and follow closely to procedures used in a previous study (see DiDomenico, 2003). The control level of the time pressure condition was defined as typing at a comfortable, self-selected pace. The low level required participants to type at a rate of 10% greater than their net typing speed as measured in a standard typing test conducted at the beginning of the experimental session. The high-level time pressure condition required participants to type at a rate of 20% greater than their net typing speed.

Dependent Variables

Several general dependent variables were investigated including assessment of perceived workload (including stress load) during trials, typing and math condition performance, muscle activity, key strike force, and wrist movements and posture.

Mental Workload, Time Pressure, and Stress Assessment

Following each trial, the participant's perception of time pressure and mental pressure was needed to identify experimental conditions perceived as being more stressful. It was necessary to know how speed increases and the addition of math questions affected feelings of time pressure, mental pressure, and stress. The Subjective Workload Assessment Technique (SWAT) scale can be used to assess time load, mental effort load, and stress load separately, and these three components may be added for an overall mental workload measure (Reid & Nygren, 1988). A modified version of the original SWAT scale employing three visual-analog scales (20cm in length) was developed for this study (Appendix D). Using continuous scales rather than the original 3-item discrete scales has been shown to be more sensitive to lower levels of mental workload (Luximon & Goonetilleke, 2001).

After each trial, participants marked a single vertical line on each scale according to their perceived levels of time load, mental effort, and stress for the preceding trial. To score the ratings, each mark was measured as a distance in centimeters from the left side of each scale. A score was obtained for each individual component (time load, mental effort load, and stress load) from 0 to 20, and the three individual scores were added together for a total workload rating from 0 to 60. Because scores are measured from the left side of the scale, a higher score reflects feelings of higher overall workload levels.

Typing Performance

Typing performance was assessed using SkillCheck software (SkillCheck, Inc.; Burlington, MA). Participants typed selected passages, and the software computed gross and net typing speed, errors per minute, and other smaller increments of errors (e.g., split words, joined words, misspelled words, etc.). Performance was measured for the entire duration of each typing trial, and a report was printed directly from the software after each trial.

Math Condition Performance

Five types of verbal responses could be elicited from the participant during the high or low math conditions. Aside from correct responses, the other possible responses (incorrect responses, no response, and “skip” or “repeat” responses) were considered errors. The total number of correct responses, the total errors, and the number of errors by type of response were tabulated.

Muscle Activity

Muscle activity was quantified using surface electromyography of the right and left arm flexor and extensor carpi ulnaris muscles (FCU and ECU), which are the main muscles used in the forearm during typing on a flat keyboard (Martin et al., 1998). To ensure EMG quality, participants were asked not to smoke, consume alcohol, or perform heavy lifting 24 hours prior to the experiment. If participants arrived for the experiment following a long walk, they were given 10 minutes to rest before electrodes were applied.

Signals were obtained using 10 mm, rectangular Ag/AgCl pregelled bipolar disposable electrodes. The skin was prepared for electrode application by shaving, slightly abrading, and cleaning the skin with alcohol to minimize impedance. Electrodes for the FCU were located one-third of the distance from the midpoint of the lateral epicondyle of the humerus and the olecranon to the styloid process of the ulna, and two fingerbreadths volar to the ulna. Electrodes for the ECU were also located one-third of the distance from the midpoint of the lateral epicondyle of the humerus and the olecranon to the styloid process of the ulna and two fingerbreadths above the ulna (Perotto, 1994; Soderberg, 1992). Interelectrode distance was set to 2.5 cm. A ground reference electrode was placed on the left medial epicondyle. Signals were transmitted through short (less than 30 cm) leads to preamplifiers (100 gain). The signals were further amplified, band-pass filtered (10-500 Hz), RMS converted (110 ms time constant), and A/D converted by hardware. No further processing or filtering was performed. The gain was set such that RMS signals did not exceed 2-3 volts. Input impedance was measured after a 15 minute electrode stabilization period and was required to be less than 10 kΩ.

After stabilization, resting and maximum voluntary exertions (MVEs) were obtained while participants sat in the same chair used for the typing tasks. The same height and armrest adjustments were maintained. For the resting EMG assessment, participants were instructed to rest their arms on the armrests and relax for a 5-second recording period. One exercise was used to test the ECU and FCU muscles simultaneously. The results of a pilot study indicated that maximum muscle activity readings were obtained during this exercise in 15 of 16 tests as compared with doing separate exercises for the ECU and FCU muscles. All MVE assessments were conducted with participants' forearms resting on the armrests. The forearms were pronated to simulate normal typing posture, and right and left muscles were tested separately. A handle was attached to a chain that was secured to a cinderblock on either side of the chair. Participants were instructed to squeeze the handlebar with the right or left hand and to pull up using only lower arm muscles (Figure 3). A 5-second ramp-up/ramp-down procedure was used in which the participant contracted his/her muscles for the first 3 seconds with the 3rd second being the maximum contraction. Seconds 4 and 5 were used to release the contraction. To pace the participants, a counter was displayed on a computer screen, and the experimenter counted aloud. Participants completed MVEs for the left and the right hand before a rest period was provided. The order of presentation between right and left arms was randomized between participants. Each exercise was repeated a minimum of 3 times, with a 45-second rest period between each trial. All EMG signals were recorded using LabView software, and the maximum RMS value for each trial was displayed. If the maximum value for either muscle occurred in the third trial, additional trials were conducted until the values were less than the maximum recorded. The maximums for each muscle across all trials were used for normalization of task EMG. Equation 1 was used to normalize all task EMG signals.

$$\% \text{ of MVE} = \frac{\text{EMG}_{\text{observed}} - \text{EMG}_{\text{resting}}}{\text{EMG}_{\text{maximum}} - \text{EMG}_{\text{resting}}}$$

Equation 1. Calculation for percent of MVE.

Figure 3. MVE testing setup.

For each trial, muscle activity was recorded continuously at a sampling rate of 512 Hz for the duration of each trial. Averages were calculated for the normalized values in 30-second increments and for the complete trial. The number of pauses or "rests" in muscle activity was also counted. A pause was defined as any break in muscle activity of 0.2 s or longer, where a break was defined as muscle activity remaining below a threshold level of three standard deviations above the recorded resting level. (McLean & Urquhart, 2002).

Key Strike Force

A Dell QuietKey keyboard was modified with two 22.2 N (5 lbf) Model LBS Series load buttons (Interface, Scottsdale, AZ) to allow key force measurements of the 'E' and 'N' keys to be obtained. The 'E' and 'N' keys are both commonly used letters, and neither is located on the home row of the keyboard. Participants were not aware of which keys had been modified although they were informed that key strike force was being measured. Each load button is 3.05

mm in height and 9.65 mm in diameter, with an accuracy of ±0.25% and a rated output of 2.0 mV/V. The load buttons were located on a metal plate beneath the keys so that pressing the 'E' or 'N' keys would allow the key to make contact with the appropriate load button. The load buttons were connected to a DMA Signal Conditioner/Amplifier with a 1.5 m integral cable. The amplifier was connected to a National Instruments terminal block (SCB 100) in order to conduct analysis using LabView software. The keyboard was modified so as not to change typing performance (Woods, 2002).

Key strike force data were recorded as voltages at 512 Hz and converted to force readings (in Newtons) using the regression equations below (Equation 2). The equations were developed by placing known weights on the appropriate keys and collecting data in the LabView program.

$$\text{E key:}\quad \text{Force (N)} = 5.6535 \times \text{Voltage (V)} - 0.0469 \quad \left(r^2 = 0.9829\right)$$
$$\text{N key:}\quad \text{Force (N)} = 9.2872 \times \text{Voltage (V)} - 0.1377 \quad \left(r^2 = 0.9487\right)$$

Equation 2. Regression equations to convert key strike forces from voltage (V) to force (N).

There were three steps in processing the data from the LabView program: determining the offset of the data, defining a cutoff point between resting and key strike values, and filtering and smoothing the data to reduce noise and make the data more interpretable. After examining the data, 0.05 V was found to be a reasonable cutoff point between key strikes and non-activation periods of the 'E' and 'N' keys, so any peaks above 0.05 V were recorded as a key strike. The value of the offset of the baseline pressure on the load cells was determined by averaging the value of the longest period of each trial that had no key strikes. Data were then filtered and smoothed using a finite-impulse response (FIR) low-pass filter with a cutoff frequency of 10 Hz. The filtering process was carried out in Matlab 6.5.1. The FIR filter coefficients were designed using the Remez function.

The data were filtered because the key force data were contaminated by 60 Hz power line noise. The noise was dominant enough that it caused multiple peaks where there should be just one for each key strike. The 10 Hz cutoff frequency was determined by the following analysis. The fastest gross speed among all participants and trials was 98.6 words per minute (wpm). With the highest average word length in any document being 5.5 characters, the fastest any person could hit consecutive keys was 9.04 hits/second (98.6 wpm × 5.5 characters per word / 60 seconds = 9.04 hits/second). Therefore, 10 Hz was a reasonable upper limit for sensing all key strikes while eliminating power line noise and other high frequency noise. The smoothing process resulted in key strikes illustrated as one peak each (Figure 4). The total number of key strikes and the force associated with each key strike were calculated for each trial.

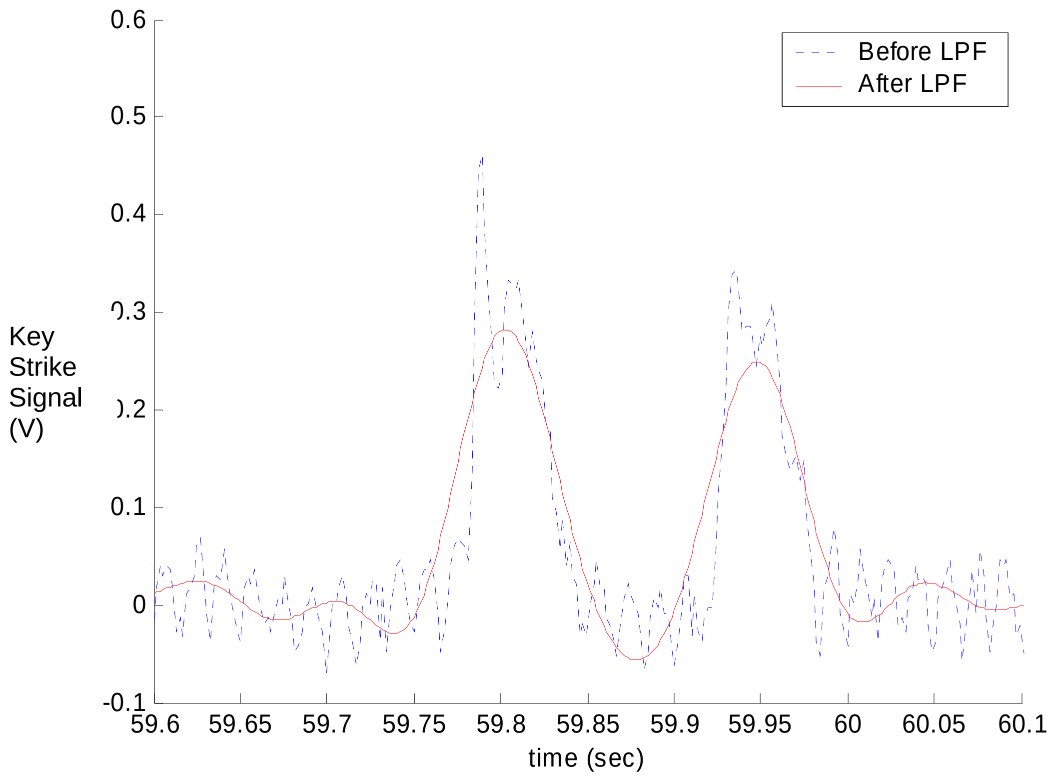

Figure 4. Illustration of key strike force before and after the low-pass filter (LPF).

Wrist Movements and Posture

Wrist angles in flexion/extension (FE) and radioulnar (RU) deviation were measured using two biaxial electrogoniometers (Model SG65; Biometrics, Ltd.; Gwent, UK). The SG65 outputs signals of ±2.3 mV to a battery-operated data logger (DataLOG Model P3X8; Biometrics, Ltd.; Gwent, UK) which outputs signals of 0.00 - 1.28 V, with a CMRR (common-mode rejection ratio) of greater than 120 dB. Data were stored on the data logger and later downloaded to a personal computer using Biometrics DataLOG PC Software 2.0 (Biometrics, Ltd.; Gwent, UK). During all trials, angles were recorded from four channels (left and right RU deviations and left and right FE angles) continuously for five minutes at 50 Hz.

Electrogoniometer endblocks were attached to each hand using the following methods. The participant's forearm was in a position that simulated typing postures (arm at participant's side and resting on a table with elbow flexed at 90°, wrist straight, and forearm pronated). A straight line was drawn on the participant's hand starting along the third metacarpal, through the wrist and out to mid-forearm to facilitate accurate placement of the end blocks. The distal end block was affixed over the metacarpal segment of each hand and secured using double-sided medical tape centered along the line on the hand. For the proper placement of the proximal end block, the participant relaxed the hand and then fully extended it with the assistance of an experimenter, The proximal end block was centered along the line on the forearm as close to the wrist as possible without distorting the spring between the end blocks and attached using double-sided tape. Medical tape was positioned over the top of the electrogoniometer end blocks to minimize external movement during testing (Hughes & Babski-Reeves, 2003).

The device was calibrated before each trial. Zero angles were set with the participant's forearm resting on the table with elbows bent at approximately 90° and hand resting flat on the table so that the forearm was pronated and the wrist was straight. Negative angles denoted extension and ulnar deviation, and positive angles corresponded to flexion and radial deviation. Data collected were averaged every 30 seconds and overall, and the total number of wrist movements, where a movement was defined as deviations of 3.5° or greater, was counted. Movements in relatively static tasks have been captured using a threshold of 3.5° in other industrial settings such as fish processing (Babski-Reeves & Crumpton-Young, 2003).

Task

Typing Task

The primary task in all trials consisted of typing a passage using the modified standard keyboard into the SkillCheck typing program. Passages were input into the program from a human resource book and were displayed to participants in hard copy on a document holder located to the left of the computer monitor. The passages were printed on one page, double-spaced so that participants did not reach the end of the document within the testing periods. All documents were on the 12th grade reading level and had an average of 5.0-5.5 characters per word. A total of 15 passages, nine for experimental trials and six for practice sessions, were available allowing for a different passage for each trial and practice session to eliminate learning effects. The order of presentation of the passages was randomized. The task was limited to the keyboard (i.e., participants were not allowed to use the mouse or to input numbers using the number pad). Using these restraints ensured that only typing movements are recorded with the EMG equipment and electrogoniometers.

The workstation was adjusted according to standard ergonomic guidelines (Eastman Kodak Company, 2004). Participants were seated in a height-adjustable chair during all practices and trials. The chair was adjusted so the forearms were parallel to the ground and the elbows were bent at approximately 90°. If needed, a footrest was provided to keep the knees bent at approximately 90°. Participants were allowed to adjust the tilt of the monitor (17-inch CRT), position of the keyboard, and placement of the document holder. However, the tilt of the keyboard was not changed between participants.

Math Task

During the trials with a low or high math condition, the experimenter stated two numbers and asked participants to state the sum for the low condition and the product for the high condition. As soon as the participant gave a response for one pair of numbers, the experimenter read the next pair of numbers. The pairs of numbers were generated randomly, and the same sequences of numbers were used for each participant. If the participant gave either an incorrect or correct answer or said “skip,” the experimenter read the next pair of numbers. If the participant did not give a response within approximately four seconds or said “repeat,” the experimenter repeated the same pair of numbers. A “skip” error was counted if the participant did not give a response to the second reading. The experimenter recorded the type of response. The experimenter and participant rehearsed the procedure briefly prior to the experimental trials.

Speed Task

Participants were asked to type 10% and 20% faster than their baseline net typing speed in the low and high speed conditions, respectively. To guide participants in how fast to type, the typing documents were marked by underlining the appropriate word to indicate where the participant should be typing every 30 seconds. There was a timer in the upper right corner of the typing screen, and a beep was emitted from the LabView program every 30 seconds to mark the time. The experimenter determined where to mark the passages by using the appropriate increased percentage of the participant's baseline net typing speed. Participants were encouraged to reach the marked word in each time increment while typing as accurately as possible. Participants were trained in the modified typing speeds prior to all experimental trials using sample documents. The baseline speed and the two levels of typing speed were practiced for two minutes each.

Trials

All trials were five minutes in duration, and participants completed nine trials. A 3-minute rest period was provided between each trial. Five minutes duration was chosen based on analysis from a pilot study which tested seven participants for ten minutes per trial combination. Using a paired t-test at a significance level of 0.05, participants showed no significant differences between the first and second half of each trial for key strike forces, wrist posture except in the right RU plane, and in right and left ECU activity. Right and left FCU activity was greater in the first half of each trial, and right RU posture was more extreme in the second half of each trial. Therefore five minutes was considered sufficient to record physiological outcomes due to added mental workload and time pressure.

Prior to the experimental trials, participants were instructed to type continuously and to answer math questions without pausing from typing. Participants used the same seating adjustments and computer equipment for each trial.

Questionnaires

Individual factors of global perceived stress and locus of control may influence the level of stress the experimental trials imposed on each participant. In turn, the degree of stress a person experienced during each trial, as measured by the SWAT scales, may have affected the magnitude of the physiological outcomes recorded.

Prior to the experimental trials, each participant completed one questionnaire to measure individual factors of perceived stress levels and locus of control. Questions pertaining to the two factors were intermingled to create a 4-page, 34-item questionnaire entitled “Personal Perceptions.” The questionnaire and details on scoring can be found in Appendix C.

Perceived Stress Scale (PSS)

The Perceived Stress Scale (PSS) measures the degree to which personal life events are viewed as stressful (Cohen, Kamarck, & Mermelstein, 1983). It is considered a global measure of stress for a relatively short period of time (one month), meaning it measures feelings of overall stress rather than stress related to a single event. The items used in the current study were taken from the questionnaire developed by Cohen, Kamarck, & Mermelstein (1983) which obtains responses on a 5-point Likert-type scale and has a coefficient alpha reliability of 0.85. Participants could have a score between 14 and 70, with higher scores indicating an increasing level of perceived stress.

Locus of Control (LOC)

Locus of Control (LOC) is an individual difference that describes the degree to which a person has external or internal reinforcement beliefs (Pettijohn, 1998). In the work environment those with an internal locus of control tend to be more satisfied with their jobs, feel less stress, view their supervisors as more considerate, and feel more in control over work tasks (Spector, 1988). An individual with an internal locus of control feels personally responsible for outcomes and for control over situations, so it is hypothesized that a person with a higher internal locus of control may experience higher levels of stress during the trials due to feelings of lack of control over the requirements of the trials. A person with a higher external locus of control may not experience as much stress because he/she does not feel as much responsibility for controlling the outcomes of the trials.

Julius Rotter’s original LOC scale has been adapted for use in many areas such as general life events, work, and safety (e.g. Jones & Wuebker, 1985; Rotter, 1966; Spector, 1988). The questions chosen for this experiment were from a general LOC questionnaire developed by Pettijohn (1998). The scale is highly correlated with the original Rotter scale ($r = 0.366$, $p < 0.001$) but has a low internal consistency ($\alpha = 0.397$) (Pettijohn, Pettijohn, & Sacco, 2004). The items have 6 choices for response ranging from "Disagree very much" to "Agree very much." The original LOC questions are forced-choice; therefore, this scale has no "neutral" response choice. Participants were classified into one of five groups reflecting the degree of internal or external LOC traits. Classification groupings followed the scoring used in Pettijohn's questionnaire (1998) and can be found in Appendix C.

Participants

Nine females and nine males, with an average age of 25.4 (6.4) years from the university community, completed the study. Participants typed an average of 52.8 (7.5) net words per minute and had no current or previous medical conditions that could affect wrist mobility, such as a previously broken wrist, carpal tunnel syndrome, or arthritis. Additionally, participants were not currently experiencing any pain, numbness, or tingling in the hands or wrists. Fifteen of the participants had an internal locus of control while the other three were rated as "both external and internal locus of control." Perceived stress ratings ranged from 27 to 44 with an average of 34.7 (5.2). Participants were grouped into three categories of perceived stress (Table 3) based on centering around the mean score and creating the size of the categories to have an approximately equal number of participants. Additional demographic information is available in Appendix E. Participants were compensated $8 per hour.

Table 3. PSS rankings.

PSS Score Range	PSS Ranking	Number of Participants
0-32	Low	6
33-37	Medium	7
38-70	High	5

Procedure

Upon arrival at the testing site, participants were given a brief description of the study and were asked to complete informed consent forms (Appendix A). A questionnaire was administered to gather demographic data on age, gender, ethnicity, relevant medical history, and typing habits (Appendix B). To determine typing abilities, potential participants were seated at the experimental setup described in the "Typing Task" section and completed at least two typing tests of two minutes in length. If the difference between the net words per minute was greater than 10%, the participant completed a third typing test. Seven of the 18 participants completed a third typing test. The average of the two or three tests was used as the participant's baseline typing speed for the trials. The SkillCheck program was used to record performance data. If participants met all criteria, electrodes were applied. During the 15-minute stabilization period, participants completed a questionnaire containing items on perceived stress and locus of control (Appendix C) and received instructions regarding the experimental trials. Participants practiced the protocol for the math questions and modified typing speeds as described in the task section. After the 15-minute stabilization period ended, impedances at the electrode sites were tested again. If any site had more than 10 kΩ impedance, the electrodes were reapplied and another 15-minute stabilization period started. Resting and MVE tests were conducted once all sites had less than 10 kΩ impedance. Upon completing the MVE tests, participants were seated at the computer workstation, and the electrogoniometer endblocks were attached to the forearms. Nine 5-minute trials were conducted with a 3-minute rest period between each trial. Participants marked the SWAT visual-analog scale with their time pressure, mental effort, and stress ratings following each trial. At the completion of the nine trials, all electrodes and electrogoniometer endblocks were removed, and participants were debriefed and compensated for their time. The duration of each experimental session was approximately 3 hours.

Analysis

Statistics on typing performance, including gross speed, net speed, total errors, misspelled words, missing words, extra words, joined words, and split words, were obtained through the SkillCheck program. The number of correct math responses and errors, including incorrect responses, no response, and requests to "skip" or "repeat", were tabulated. Overall averages were calculated for EMG RMS signals, key strike force, and wrist position. The number of EMG gaps, where a gap is any period of inactivity longer than 0.2 s, and the total number of deviations in wrist posture greater than 3.5° were counted.

Appropriate descriptive statistics were calculated for all dependent variables. Normality tests were performed, using the Shapiro-Wilk's test, prior to analysis. The general criteria for determining if a dependent variable would be included in the ANOVA were having five of nine trials distributed according to a normal distribution ($p = 0.05$) and inspecting the histogram for each dependent measure.

A mixed-factors ANOVA was used to test for the effects of trial order, independent variables, gender, locus of control ratings, and perceived stress ratings (Figure 5). Results were considered significant at an alpha level of 0.05.

$$Y_{ijklmnopq} = \mu + \alpha_i + \beta_j + \psi_k + \delta_l + \phi_m + \lambda_n + \omega_o + \gamma_{p(ijkl)} + \phi\gamma_{mp(ijkl)} + \lambda\gamma_{np(ijkl)} + \omega\gamma_{op(ijkl)} + \varepsilon_{q(ijklmnop)}$$

Between Subjects	Within Subjects
Gender (G, α)	Time Pressure (T, ϕ)
Perceived Stress (P, β)	Mental Workload (M, λ)
Locus of Control (L, ψ)	Time Pressure x Mental Workload (R, ω)
Order (O, δ)	Error (interaction with S/GPLO)
Subjects (S/GPLO, γ)	

Figure 5. Mixed-factors ANOVA model

Any significant differences found were further analyzed using Tukey HSD tests to determine which levels produced significant differences, where appropriate. T-tests were used to evaluate differences in math performance because there were only two levels of responses for math questions: addition and multiplication. Specific typing and math errors and EMG gap counts were not normally distributed; therefore, Friedman's 2-way ANOVAs were used for specific typing and math errors and for EMG gap counts to determine any significant differences between factor levels. Post-hoc comparisons were computed using methods given by Siegel and Castellan (1988). T-test and Friedman's 2-way ANOVA results were also considered significant at an alpha level of 0.05.

Spearman correlation coefficients were calculated for dependent variables to determine relationships. Only variables measured at all three condition levels were considered; therefore, performance on addition and multiplication questions was not included in the correlation matrix. The 44 dependent variables were grouped into categories (muscle activity, EMG gaps, key strike forces, total key strikes, wrist deviations, wrist posture, typing performance, and SWAT ratings) and classified as having significant positive or negative correlations with all other variables in the category, at least one other variable, or no other variable. Correlations were considered significant at $p \leq 0.001$, which corresponded approximately to $|r| \geq 0.26$.

Results

On average, participants typed at a gross speed of 59.0 (11.5) wpm and at a net speed of 41.4 (11.7) wpm. They made an average of 30 (18.7) typing errors per trial. Participants were able to answer slightly more addition questions than multiplication questions, and participants did rate the trials as having fairly high workload. The ECU muscles displayed more activity than the FCU muscles. The right ECU was more active than the left ECU, but the left FCU was more active than the right FCU. In general, the FCU had more periods of muscular rest than the ECU. Mean key strike forces ranged from 1.55 N to 1.81 N. Average wrist postures were 6.9° ulnar deviation of the right hand, 10.3° of radial deviation for the left hand, and around 30° extension for both hands. Wrist deviations occurred at a rate of 86 deviations per minute in the radioulnar plane and over 200 deviations per minute in the flexion/extension plane. Complete means and standard deviations for each dependent variable are listed in Table 4.

Table 4. Averages and total counts (standard deviations) for dependent variables.

Independent Variable	Average or Total Count per Trial	Independent Variable	Average or Total Count per Trial
Right ECU average	0.143 (0.055)	Right RU deviation	428.84 (255.18)
Right FCU average	0.070 (0.041)	Right FE deviation	1048.46 (525.55)
Left ECU average	0.130 (0.052)	Left RU deviation	448.14 (213.31)
Left FCU average	0.077 (0.041)	Left FE deviation	1110.15 (464.35)
Right ECU median	0.126 (0.049)	Gross Speed	58.952 wpm (11.471 wpm)
Right FCU median	0.058 (0.037)	Net Speed	41.382 wpm (11.654 wpm)
Left ECU median	0.121 (0.047)	Overall Errors	29.593 (18.670)
Left FCU median	0.063 (0.036)	Missing Words	2.895 (1.563)
Right ECU gaps	11.222 (35.846)	Extra Words	0.679 (1.107)
Right FCU gaps	70.765 (109.998)	Joined Words	0.426 (0.629)
Left ECU gaps	0.574 (3.494)	Split Words	0.327 (0.639)
Left FCU gaps	42.469 (62.394)	Misspelled Words	25.080 (16.842)
‘E’ average	1.599 N (0.376 N)	No Response (math)	0.556 (1.596)
‘N’ average	1.755 N (0.508 N)	Repeat (math)	1.824 (2.355)
‘E’ median	1.610 N (0.385 N)	Skip (math)	0.843 (2.297)
‘N’ median	1.751 N (0.518 N)	Wrong (math)	1.926 (1.812)
‘E’ max	2.390 N (0.473 N)	Total Math Errors	5.148 (3.614)
‘N’ max	2.682 N (0.684 N)	Correct (Math)	46.352 (13.047)
‘E’ strikes	137.957 (34.551)	Time Stress	13.629 (5.642)
‘N’ strikes	88.062 (22.867)	Math Stress	12.677 (5.490)
Right RU average	-6.876° (8.417°)	Anxiety	10.689 (5.594)
Right FE average	-30.582° (11.210°)	Total Stress	36.996 (14.502)
Left RU average	10.277° (5.665°)		
Left FE average	-32.092° (11.104°)		
Right RU median	-6.978° (8.397°)		
Right FE median	-30.877° (11.219°)		
Left RU median	9.804° (5.657°)		
Left FE median	-32.505° (11.100°)		

Trial order, gender, perceived stress ratings, and locus of control rankings were not significant factors for any dependent variable measured. With the exception of EMG gap counts and specific typing and math errors, all dependent variables were considered normally distributed (Appendix F) and were included in the ANOVA. All specific *p*-values for each dependent variable are listed in Table 5 with significant values highlighted. Averages and significant differences for subsequent Tukey HSD analyses are listed in Appendix G and discussed in the following sections. Friedman’s 2-way ANOVA *p*-values for EMG gap counts and specific typing and math errors are listed in Table 6 along with appropriate post-hoc comparisons.

Results

Table 5. ANOVA *p*-values.

Dependent variables	Order	Gender	PSS ranking	LOC ranking	Time Pressure	Mental Workload	Time Pressure* Mental Workload
Right ECU mean	0.9983	0.4591	0.1526	0.6845	0.0681	<0.0001	0.2302
Right FCU mean	0.9977	0.0697	0.4274	0.3538	0.0376	<0.0001	0.0461
Left ECU mean	0.9956	0.2096	0.3020	0.7246	0.7570	0.1257	0.5354
Left FCU mean	0.9446	0.8434	0.1920	0.9152	0.0637	0.0002	0.9327
Right ECU median	0.9965	0.2807	0.1428	0.6044	0.0522	<0.0001	0.1133
Right FCU median	0.9982	0.0884	0.4450	0.2271	0.0422	<0.0001	0.0811
Left ECU median	0.9942	0.2516	0.2160	0.7593	0.9729	0.0155	0.2852
Left FCU median	0.8800	0.8840	0.2249	0.7115	0.0835	<0.0001	0.9334
E key mean force	0.9903	0.7814	0.2216	0.0612	0.0008	0.2533	0.3911
N key mean force	0.9990	0.3328	0.1949	0.1403	0.0040	0.0008	0.5743
E key median force	0.9923	0.8834	0.2177	0.0793	0.0003	0.4840	0.3659
N key median force	0.9996	0.3480	0.1855	0.1666	0.0010	0.0044	0.4064
E key maximum force	0.9312	0.7588	0.1215	0.0872	0.0044	0.0336	0.5900
N key maximum force	0.9847	0.3203	0.2439	0.1184	0.0569	0.1472	0.6219
E key strikes (total)	0.9863	0.4256	0.4325	0.1785	0.0166	<0.0001	0.7844
N key strikes (total)	0.9963	0.4411	0.4805	0.1482	0.1006	<0.0001	0.4345
Right RU mean	0.9604	0.1564	0.8482	0.9513	0.5051	0.9995	0.6603
Right FE mean	0.9232	0.8781	0.3489	0.9641	0.4390	0.0871	0.6199
Left RU mean	0.8306	0.9974	0.4800	0.6120	0.9627	0.0116	0.9524
Left FE mean	0.9823	0.8139	0.6080	0.7892	0.1034	0.1437	0.9331
Right RU median	0.9512	0.1528	0.8502	0.9110	0.5027	0.9911	0.6527
Right FE median	0.9253	0.8584	0.3719	0.9186	0.4246	0.0929	0.6135
Left RU median	0.8369	0.9402	0.4951	0.6254	0.9741	0.0141	0.9594
Left FE median	0.9836	0.8424	0.6172	0.8031	0.0734	0.1714	0.9220
Right RU deviations	1.0000	0.1077	0.5174	0.2604	0.5909	0.0003	0.4390
Right FE deviations	0.9994	0.0885	0.8400	0.1019	0.0045	<0.0001	0.0483
Left RU deviations	0.9926	0.2525	0.6919	0.3272	0.0759	<0.0001	0.8550
Left FE deviations	0.9817	0.0550	0.7465	0.0515	0.0102	<0.0001	0.0134
Gross speed	0.9825	0.4096	0.4725	0.1177	0.0188	<0.0001	0.0661
Net speed	0.8915	0.5494	0.4511	0.2492	0.0741	<0.0001	0.9996
Overall typing errors	0.8363	0.1953	0.3183	0.6679	0.0009	0.7836	0.3365
Time load	0.9625	0.6356	0.1496	0.8192	0.0065	<0.0001	0.5715
Mental effort load	0.9902	0.9707	0.9156	0.3408	0.0781	<0.0001	0.6135
Stress load	0.4881	0.5564	0.9878	0.2188	0.3076	<0.0001	0.8661
Overall workload	0.9892	0.9652	0.6208	0.3854	0.0095	<0.0001	0.5966

Table 6. Friedman's ANOVA *p*-values.

Dependent Variable	Mental Workload	Significant Pairs*	Time Pressure	Significant Pairs*	Interaction	Significant Pairs* (Speed/Math combinations)
No Response (math)	0.0196	H-L	0.0646		0.0293	
Repeat (math)	0.2367		0.9290		0.6004	
Skip (math)	0.0017	H-L	0.5171		0.0053	
Wrong (math)	0.0578		0.0494	C-L	0.0328	
Extra Words	0.0059	L-C	0.0323	H-C	0.0011	
Misspelled Words	0.0920		<0.0001	H-C, H-L	0.0002	H/L-C/L, H/C-C/C, H/C-C/L, H/C-C/H
Missing Words**	0.0033	H-C, L-C	0.0337	H-L	0.5717	
Joined Words	0.2446		0.9923		0.3468	
Split Words	0.3916		0.1241		0.4907	
Right ECU EMG gaps	0.0560		0.7529		0.1700	
Right FCU EMG gaps	0.0007	L-C, H-C	0.7917		0.0010	
Left ECU EMG gaps	0.5188		0.8825		0.9016	
Left FCU EMG gaps	0.0026	H-C	0.8900		0.0110	HH-HC

C: Control
L: Low
H: High

* Level with highest value listed first.
**ANOVA results (data normally distributed)

Effects of Mental Workload

As measured by responses to the SWAT scales, the presence of addition or multiplication questions (low and high mental workload levels) significantly increased participants' perceived levels of time load, mental effort load, stress load, and overall workload when compared to the control condition of no math questions. However, there was no significant difference in SWAT ratings between multiplication and addition (Figure 6).

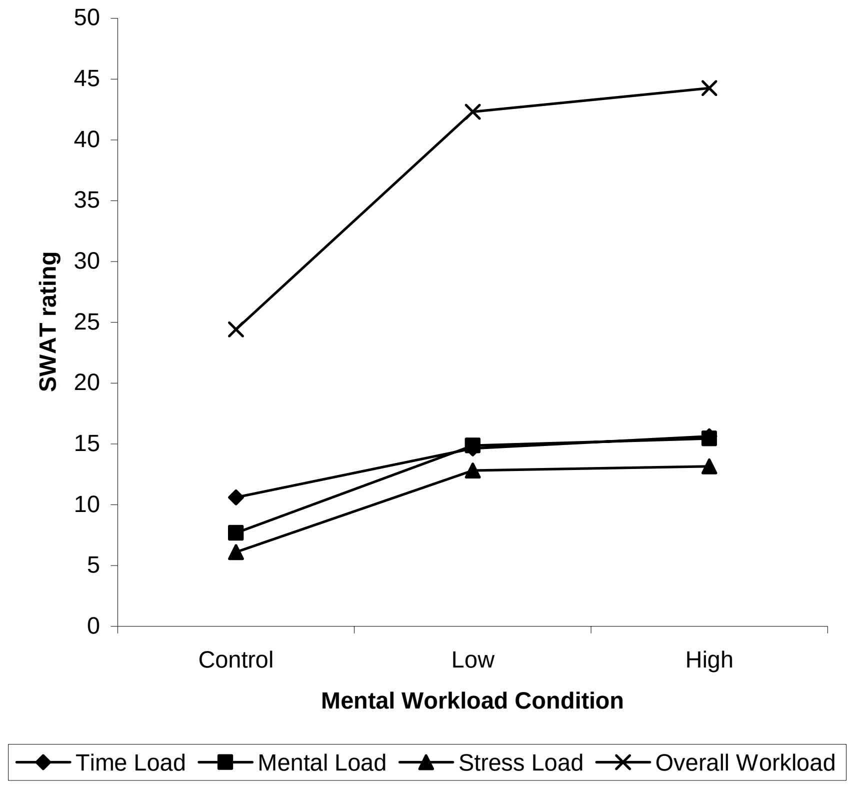

Figure 6. Average SWAT ratings for mental workload conditions.

Gross typing speed significantly decreased as the level of mental workload increased. Although net typing speed decreased significantly between the control condition and the two conditions with math questions, there was no difference between the low and high conditions (addition versus multiplication). Total typing errors were not affected by changes in mental workload (Figure 7), but missing words and extra words were significantly higher in the control condition than the low condition. Missing words were significantly higher in the high level than the control level, but the high level was not significantly different from the other levels for other typing performance measures.

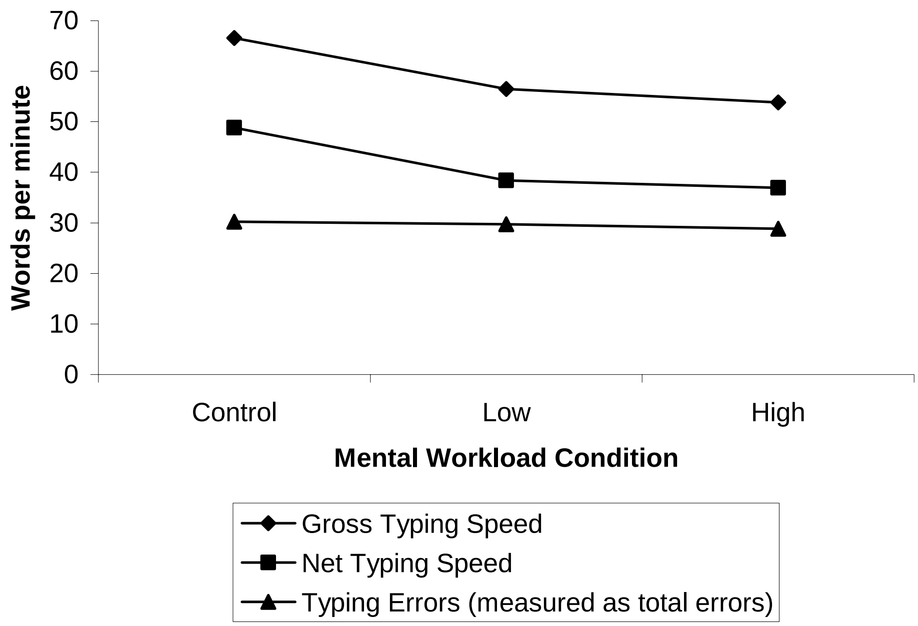

Figure 7. Average typing performance for mental workload conditions.

With the exception of mean and median left ECU activity, muscle activity was significantly lower for trials with addition or multiplication than for control conditions. There were no significant differences between addition and multiplication. Mean left ECU activity showed no significant differences with mental workload, and median left ECU displayed significantly higher activity in the control condition than in the high mental workload condition (Figure 8). The number of pauses, or EMG gaps, in the FCU muscles was significantly higher in the low condition than the control condition. Left FCU EMG gaps were also significantly higher in the high condition than in the control condition. Other EMG gap measures were not affected by mental workload.

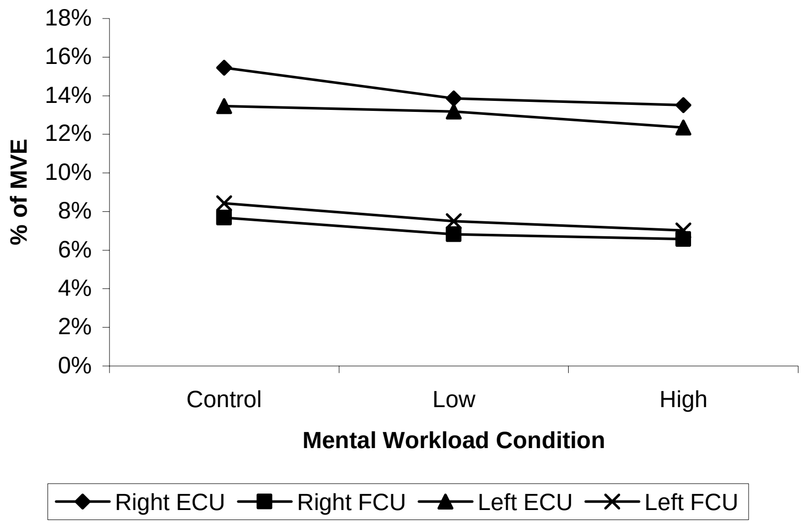

Figure 8. Average muscle activity for mental workload conditions.

Mean and median 'N' key strike force and maximum 'E' key strike force had significantly higher values in the low level mental workload than the control condition. The high level also had lower values than the low level but was not statistically significant. Mean and median 'E' key strike force and maximum 'N' key strike force showed no significant differences between mental workload conditions (Figure 9). The total number of 'E' key strikes significantly decreased as the mental workload level increased for each condition, and the high level of mental workload had significantly less 'N' key strikes than the control or low level (Figure 10).

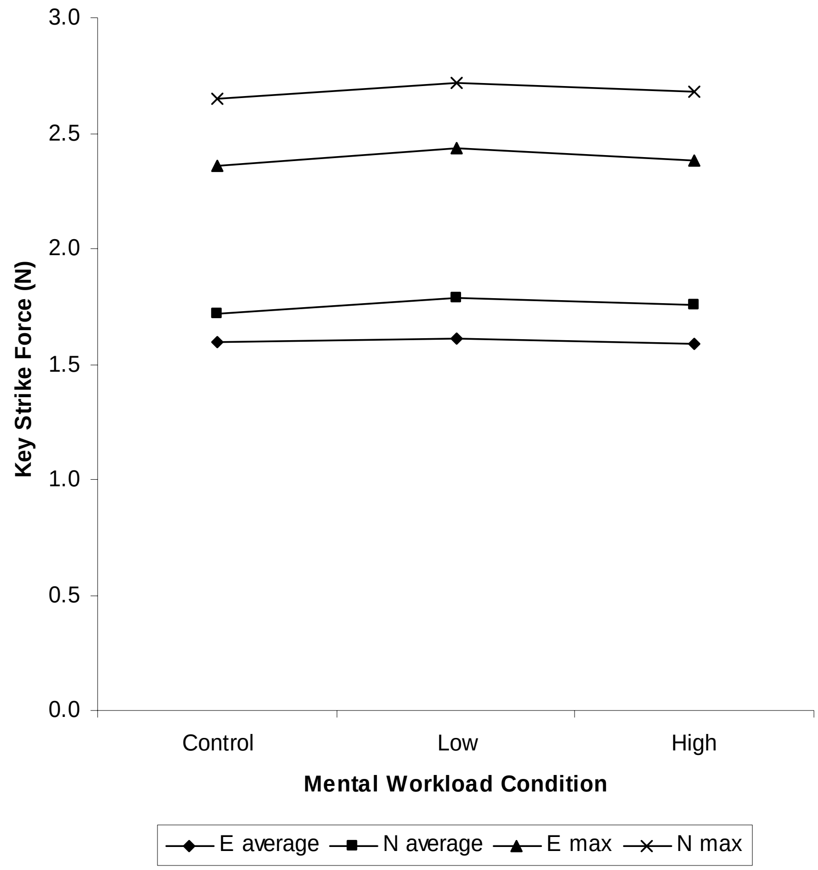

Figure 9. Average and maximum key strike forces for mental workload conditions.

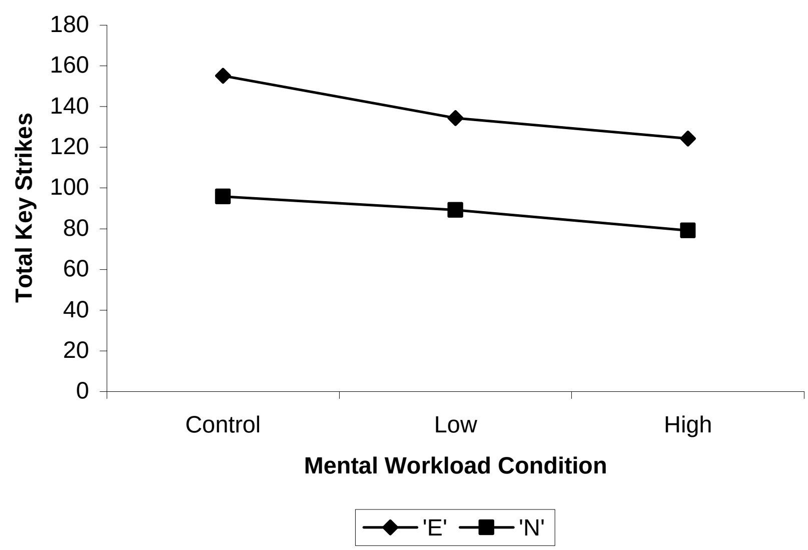

Figure 10. Total key strikes for mental workload conditions.

Results

The number of wrist deviations for both hands and both planes of motion were significantly higher in the control condition than either the low or high condition. There was no significant difference in wrist movement between addition and multiplication conditions (Figure 11). The only significant difference in wrist posture was found in left radioulnar movements where trials with addition had significantly less deviated postures than the control condition (Figure 12). Higher levels of mental workload also led to less extreme postures of the right FE plane although this was not statistically significant (p = 0.0871 and 0.0929 for the mean and median).

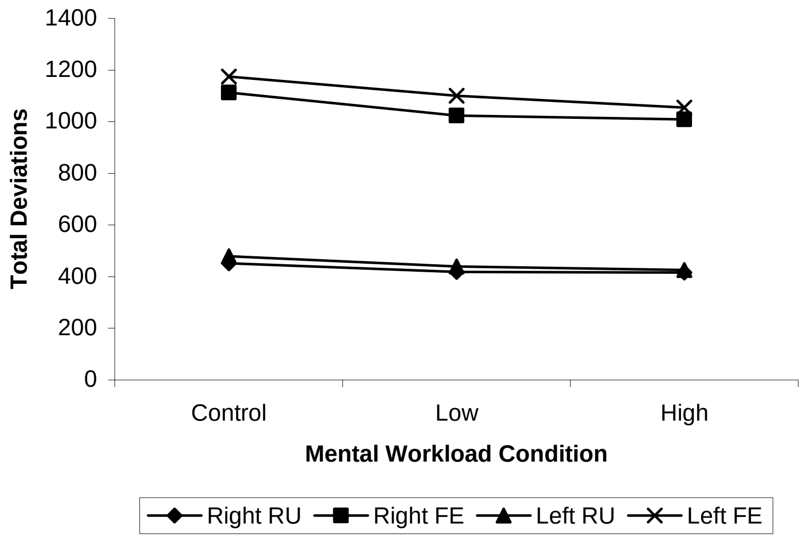

Figure 11. Total wrist deviations for mental workload conditions.

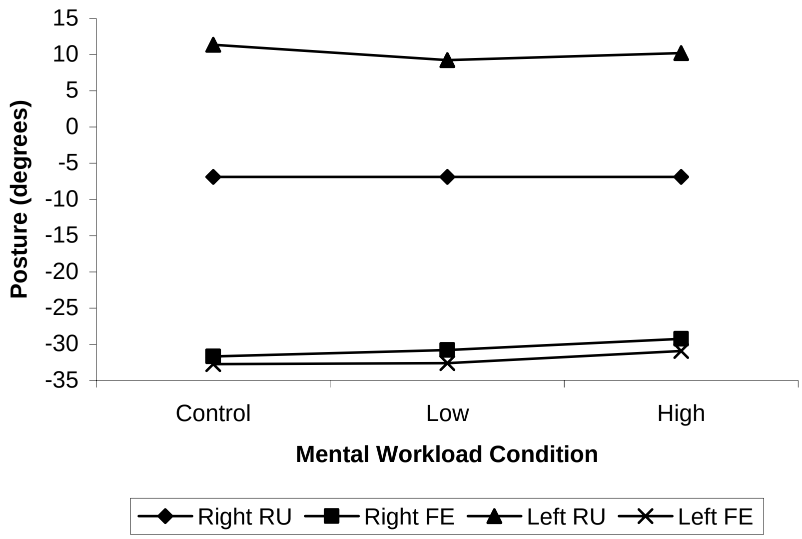

Figure 12. Wrist posture for mental workload conditions.

Effects of Time Pressure

Increases in time pressure resulted in significantly higher perceived levels of time load and overall workload but not in mental effort load and stress load as measured by the SWAT ratings at the conclusion of each trial. However, there were no significant differences in SWAT ratings between low and high conditions (Figure 13).

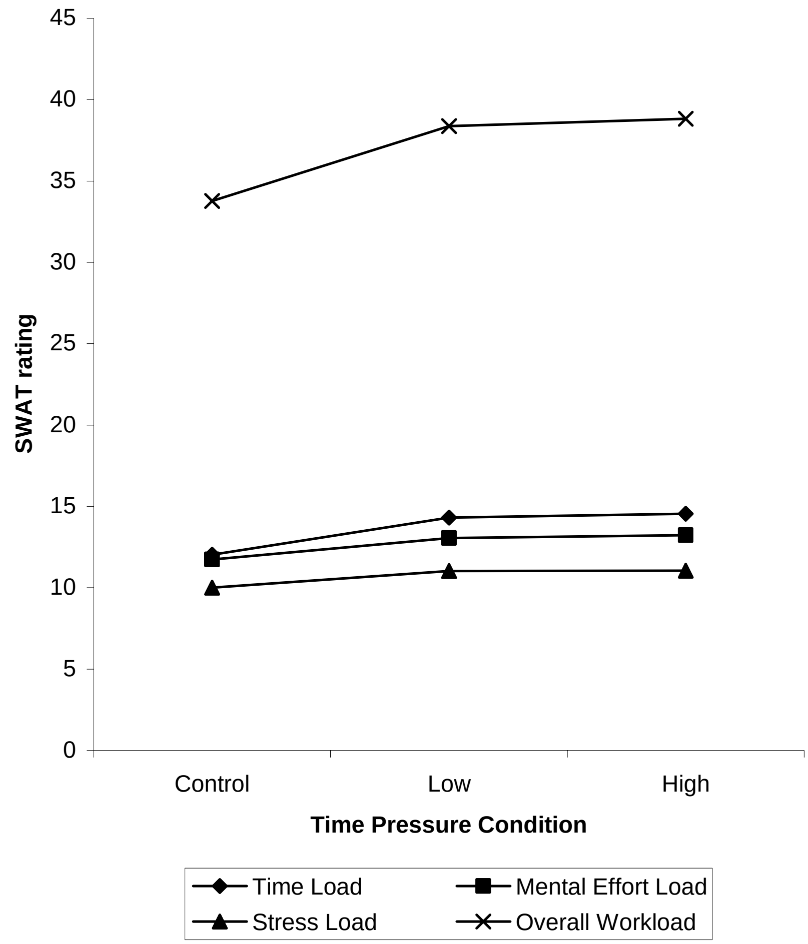

Figure 13. SWAT ratings for time pressure conditions.

Gross speed was significantly higher for the high time pressure condition than the control condition, although net speed appeared to be unaffected by time pressure (Figure 14). Overall typing errors were significantly higher under high time pressure than for both the control and low time pressure conditions. There were more extra words in the high time pressure condition than in the control condition, and there were more misspelled words in the high time pressure condition than in the low condition.

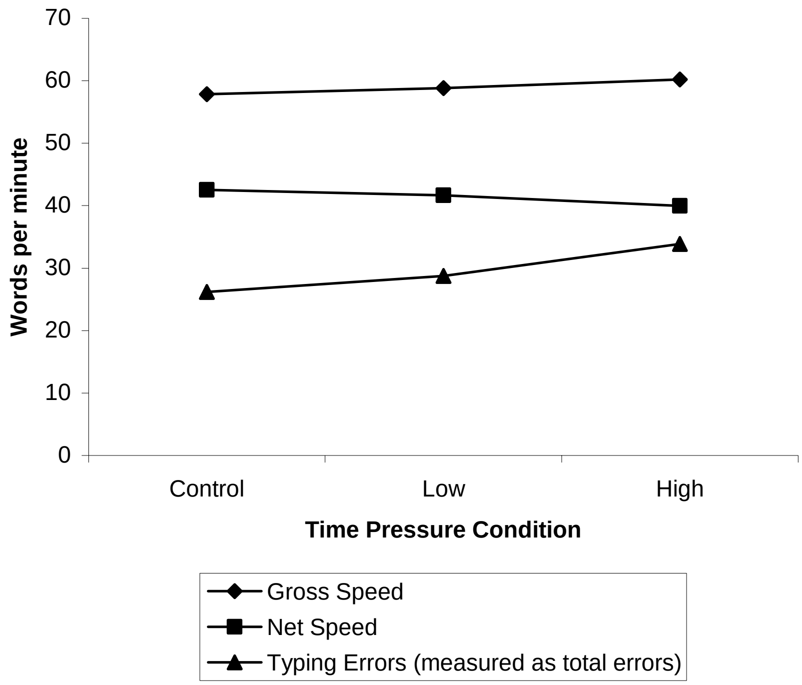

Figure 14. Typing performance for time pressure conditions.

Two measures, total correct responses and total errors, were analyzed for differences between addition and multiplication using t-tests (*p*-values listed in Appendix H). The total number of addition questions answered correctly was significantly higher than multiplication questions correctly answered overall and for each time pressure level (Figure 15). The number of multiplication errors was significantly higher than addition errors overall, for the control time pressure condition and for the high time pressure condition. Multiplication errors were higher than addition errors for the low time pressure condition, but the value was not significantly different (Figure 16). The results of the Friedman's ANOVA showed significantly more "no response" and "skip" errors during trials with multiplication than during trials with addition. Level of time pressure (evaluated as a one-way ANOVA for the three levels) did not significantly affect correct responses or number of total errors for either addition or multiplication, but there were actually significantly more wrong answers in the control condition than in the low level of time pressure.

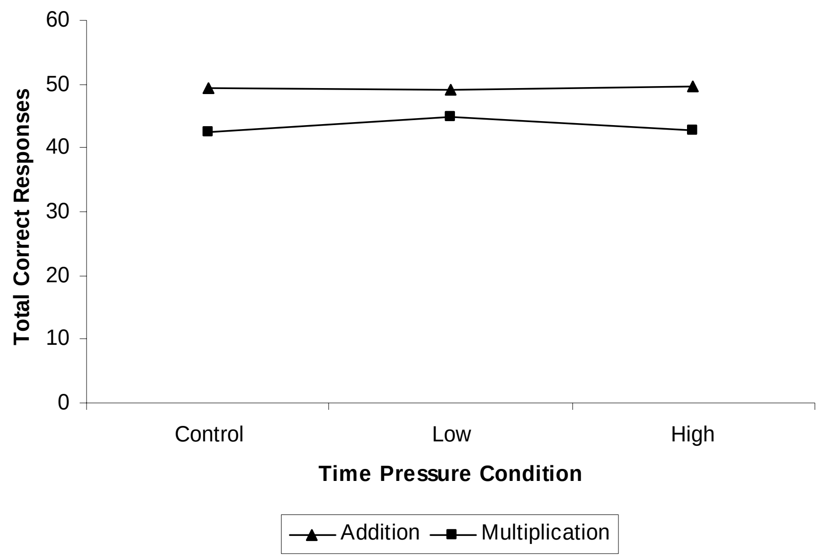

Figure 15. Total correct math responses.

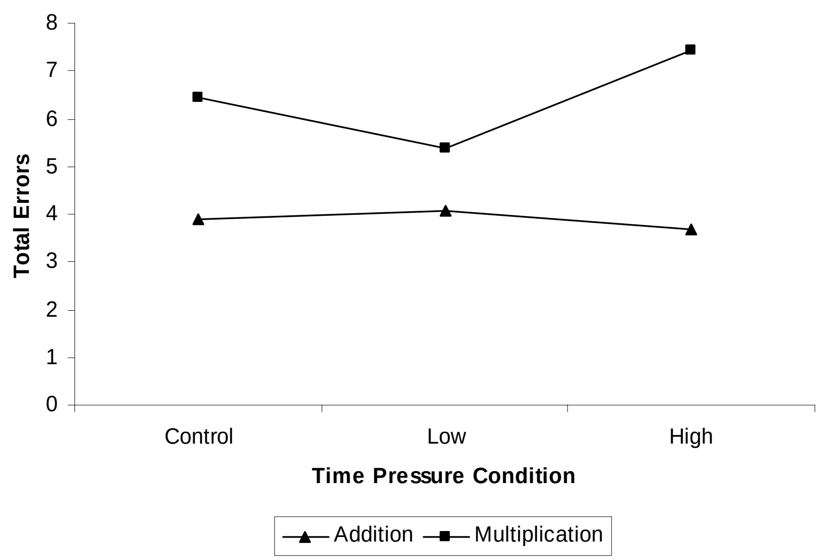

Figure 16. Total math errors.

Increases in time pressure resulted in increases of muscle activity. Right FCU mean and median activity was significantly higher during the high time pressure condition than in the control condition. The same pattern was present for measures of the right ECU and left FCU but was not statistically significant (Figure 17). The low time pressure condition showed no significant differences for any measures of muscle activity. Time pressure did not significantly affect any EMG gap counts.

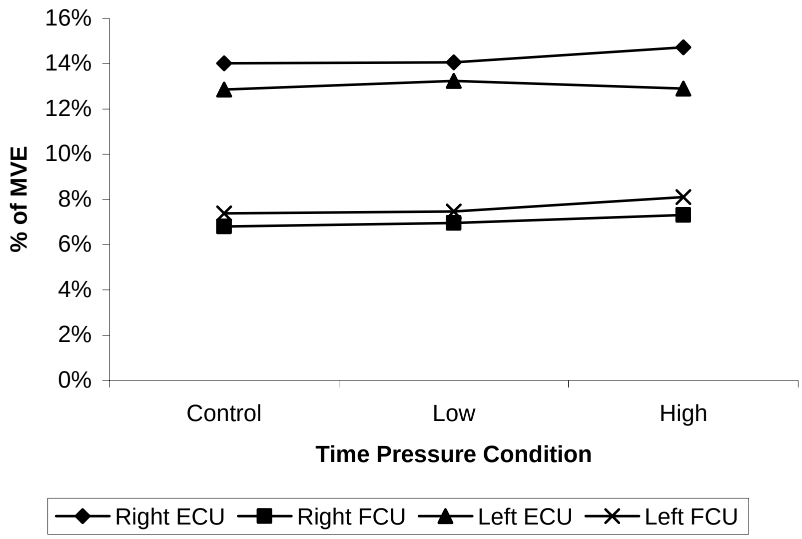

Figure 17. Average muscle activity for time pressure conditions.

With the exception of the maximum value recorded for the ‘N’ key ($p = 0.0569$), mean, median, and maximum key strike forces increased as time pressure increased. The high time pressure condition had significantly higher values than the control condition with the exception of ‘N’ key maximum values (Figure 18). The number of ‘E’ key strikes was significantly higher in the high time pressure condition than in the control condition (Figure 19). The low time pressure condition was not significantly different from the control or high conditions.

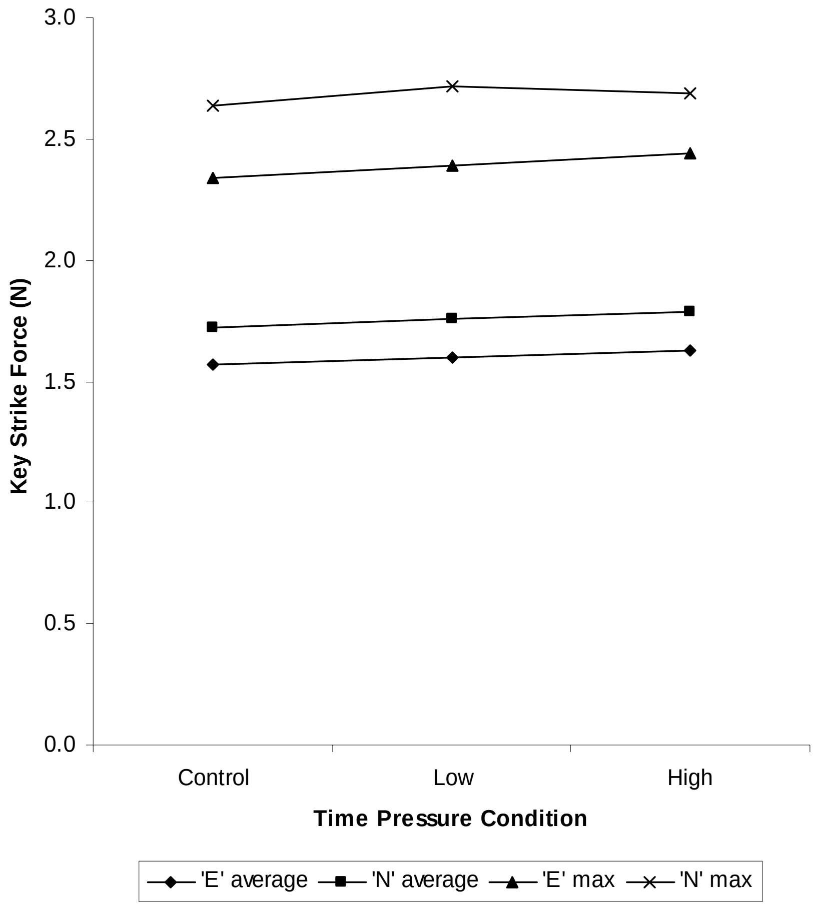

Figure 18. Average and maximum key strike force for time pressure conditions.

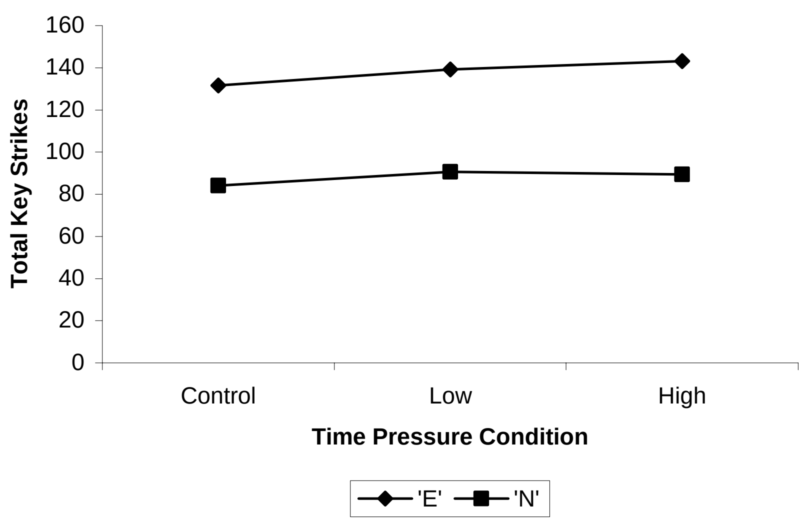

Figure 19. Key strikes for time pressure conditions.

The number of flexion/extension (FE) movements significantly increased with increases in time pressure, but the number of radioulnar movements was not significantly affected by time pressure. The number of left FE deviations was significant higher at the high time pressure condition than the control condition, and the number of right FE deviations was significantly higher in the high time pressure condition than both the control and low time pressure conditions (Figure 20). Time pressure had no significant effects on wrist posture.

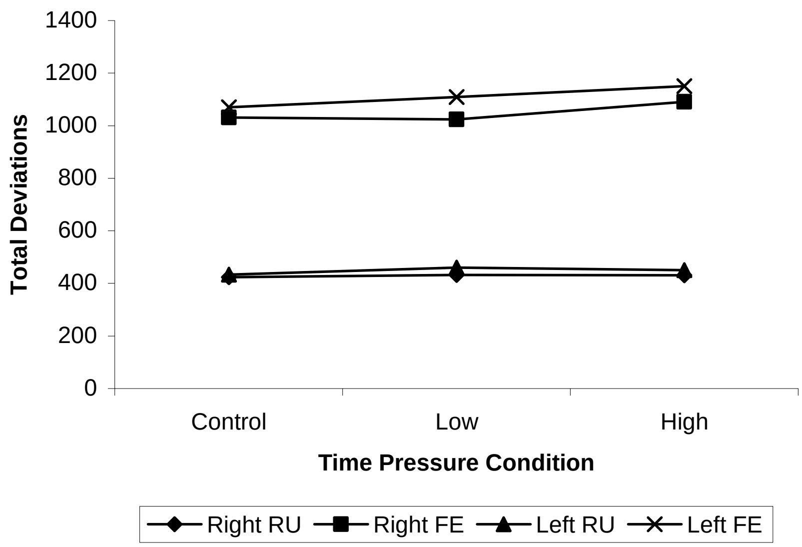

Figure 20. Total wrist deviations for time pressure conditions.

Effects of Mental Workload and Time Pressure Interaction

An interaction effect between mental workload and time pressure was found for mean right FCU muscle activity. Muscle activity increased with time pressure increases but decreased as mental workload increased (Figure 21). There was a significant interaction effect between mental workload and time pressure for flexion/extension movements in both hands. Deviations decreased as mental workload increased, but deviations increased as time pressure increased (Figure 22). In both interactions the increases seen with one factor are muted by the decreases of the other factor when the factors are considered together.

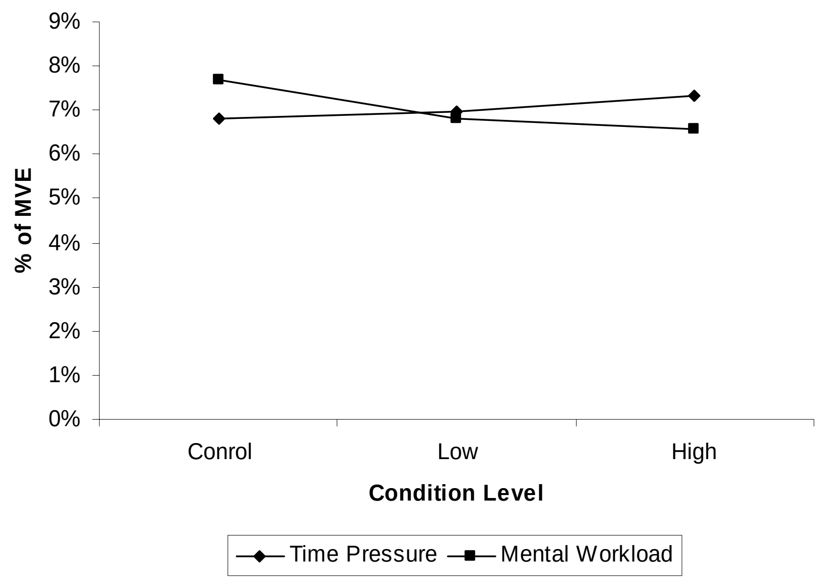

Figure 21. Interaction of time pressure and mental workload on mean right FCU activity.

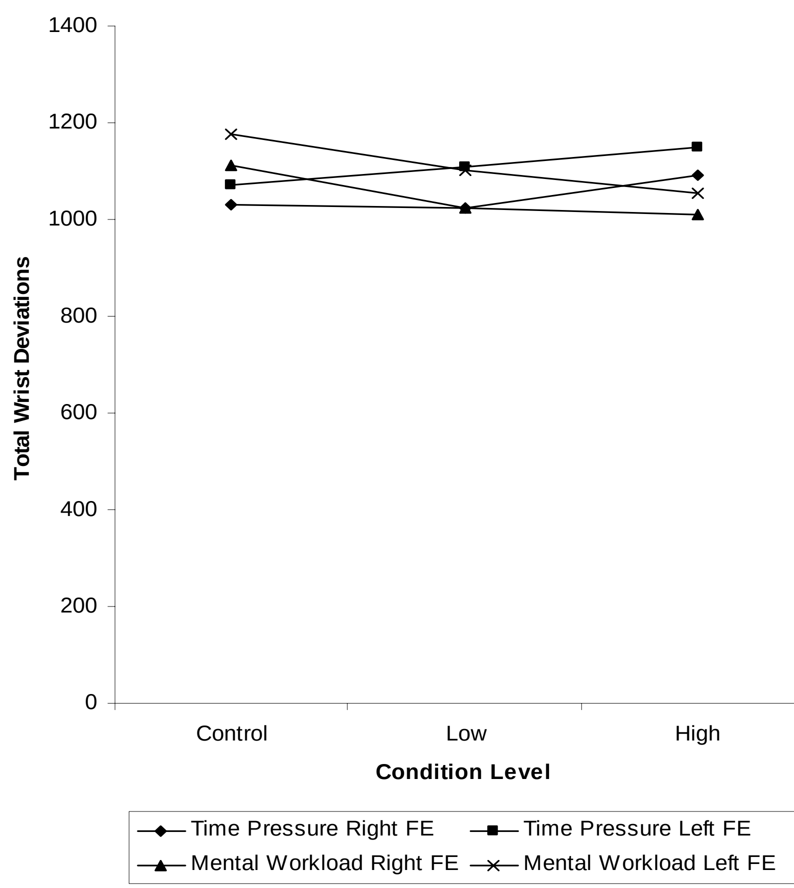

Figure 22. Interaction effects of time pressure and mental workload on left and right FE deviations.

Results

The only significant interactions from the Friedman's ANOVA were found for misspelled words and left FCU gaps. Higher levels of time pressure increased the number of misspelled words and decreased the number of EMG gaps, while higher levels of mental workload decreased misspelled words and increased the number of EMG gaps (Figure 23, Figure 24). This caused an effect similar to the interactions found in right FCU muscle activity and left and right FE deviations: taken together, mental workload and time pressure tend to "cancel" each other. This observation can be explained by changes in typing speed. Typing speed is correlated positively with the number of typing errors including misspelled words and negatively with the number of EMG gaps.

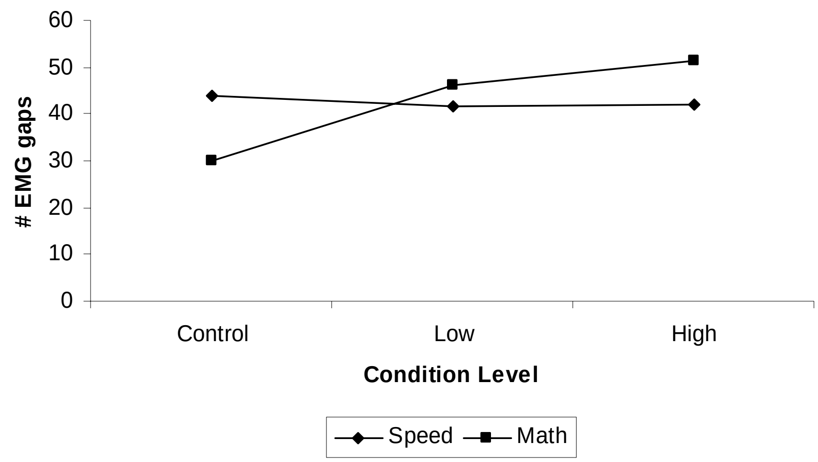

Figure 23. Left FCU EMG gaps.

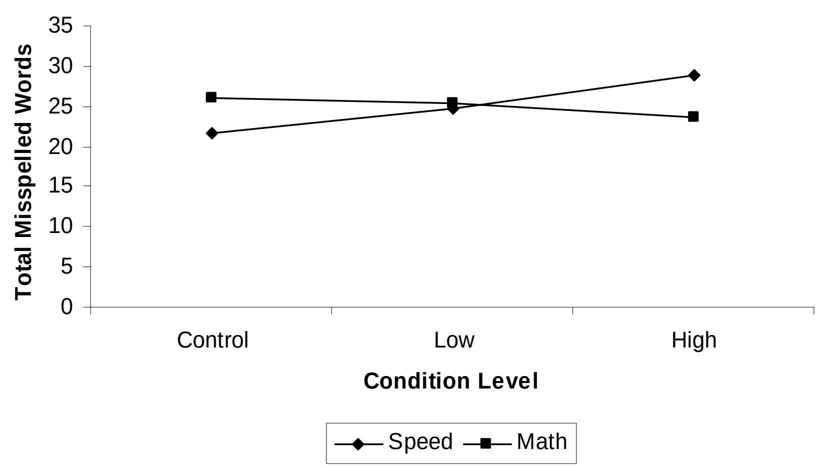

Figure 24. Misspelled words.

Correlations

Table 7 summarizes the nature of the correlations ($p \leq 0.001$, $|r| \geq 0.26$) between the dependent variable categories. Note that "Some" indicates at least one variable was correlated and that increases in wrist posture were associated with more extreme angles. The correlations are discussed in detail in the following section.

Table 7. Correlations between dependent variable categories ($p \leq 0.001$)

	Muscle Activity	EMG Gaps	Key Strike Forces	Total Key Strikes	Wrist Deviations	Wrist Posture	Typing Performance	SWAT Ratings
Muscle Activity	All +	All -	Some -	No	Some +	Some +	Some +	Some -
EMG Gaps		Some +	Some -	No	Some -	No	Some + & -	Some +
Key Strike Forces			All +	Some -	Some +	Some +	Some -	Some +
Total Key Strikes				All +	No	No	All +	All +
Wrist Deviations					All +	Some +	Some +	No
Wrist Posture						Some +	No	No
Typing Performance							All + & -	Some -
SWAT Ratings								All +

Variables included in each grouping:
Muscle Activity: Right and left ECU and right and left FCU means and medians
EMG Gaps: Right and left ECU gaps and right and left FCU gaps
Key Strike Forces: 'E' and 'N' mean, median, and maximum key strike forces
Total Key Strikes: 'E' and 'N' total key strikes per trial
Wrist Deviations: Right and left RU and right and left FE deviations
Wrist Posture: Right and left RU and right and left FE means and medians
Typing Performance: Gross speed, net speed, and overall typing errors
SWAT Ratings: Time load, mental effort load, stress load, and overall workload

Muscle Activity

Measures of muscle activity were positively correlated with each other while muscle activity and EMG gaps were negatively correlated. The only strong correlation between key strike force and muscle activity was in median right FCU decreasing as average, median, and maximum force on 'E' key strikes increased (r = -0.292, -0.295, and -0.263). There were no strong correlations between the number of key strikes and muscle activity. With the exception of left FE deviations, muscle activity increased as the number of wrist movements increased (*r*-values range from 0.266 to 0.549). Overall, muscle activity increased as wrist posture became more extreme. The only exception was in left RU posture, which did not correlate with muscle activity. Interestingly, more extreme postures of the right hand corresponded to higher muscle activity in the left hand. Increases in both ECU muscles corresponded with increases in net speed (*r* = 0.323 and 0.360). Gross speed was correlated with increases in right ECU (*r* = 0.287) and left FCU muscles (*r* = 0.270), and overall errors increased along with muscle activity of the left FCU (*r* = 0.274). Finally, left ECU muscle activity decreased as total perceived workload increased (*r* = -0.273).

EMG gaps

Right ECU gaps were positively correlated with right FCU gaps (*r* = 0.676) and left ECU gaps (*r* = 0.292), but there were no other significant correlations within EMG gaps. As the number of rest periods in the left FCU decreased, all key strike force measures for both the ‘E’ and ‘N’ key increased (*r*-values -0.385 to -0.463). In general wrist deviations increased as the number of rest periods in muscle activity decreased. The number of wrist deviations increased in both hands and both planes of motion as the number of right FCU gaps decreased (*r*-values -0.333 to -0.456). Also, left FE deviations increased as left FCU gaps decreased (*r* = -0.362), and right FE deviations increased as right ECU gaps decreased (*r* = -0.312). For typing performance measures, the number of rest periods in the left FCU increased as overall errors increased (*r* = 0.311) and net speed decreased (*r* = -0.307). Right FCU gaps decreased when gross and net typing speeds increased (*r* = -0.323 and -0.293). Finally, mental load, time load, and overall workload increased along with right FCU gaps (*r* = 0.321, 0.273, and 0.341), and right ECU gaps increased along with mental load (*r* = 0.265).

Key Strike Forces

All key strike forces were correlated positively with each other. Increases in all ‘N’ key force measures corresponded with decreases in the number of ‘E’ and ‘N’ key strikes. Increases in ‘E’ key strike forces were correlated with more deviations in the left FE and RU planes of motions (*r* = 0.495 and 0.338), and maximum ‘N’ key strike force was also associated with an increase in left FE deviations (*r* = 0.337). Increases in ‘E’ average and median forces were correlated with more extreme right RU postures (*r* = -0.282 and -0.293). All ‘N’ key strike force measures increased as gross speed decreased (highest *r*-value -0.500), and time load and overall workload increased when average and median 'N' forces increased (highest *r*-values 0.300 and 0.258).

Total Key Strikes

'E' and 'N' key strikes were positively correlated with each other, and they increased as gross speed, net speed, and overall typing errors increased (*r*-values from 0.297 to 0.890). 'E' and 'N' key strikes decreased as time load, mental effort load, stress load, and overall workload increased (*r*-values from -0.291 to -0.473).

Wrist Deviations

Wrist deviations in both hands and planes of motion increased with each other. Increases in deviations were generally associated with more extreme wrist postures. Increases in right RU and FE deviations were correlated with more extreme postures of the right RU plane and right and left FE (*r*-values from 0.326 to 0.530). Increases in left RU deviations were associated with more extreme postures of the left and right FE plane (*r*-values from 0.260 to 0.328), and left FE deviations increased along with more extreme left FE postures (r = 0.411). Increases in gross speed were correlated with higher left RU deviations (r = 0.269), and increases in net typing speed were correlated with higher FE deviations (r = 0.290).

Wrist Posture

Flexion/extension postures of both hands were positively correlated (*r*-values from 0.651 to 0.658), but radioulnar postures were not significantly correlated.

Typing Performance

Gross and net typing speeds were positively correlated (r = 0.599). Overall errors increased as gross speed increased (r = 0.425), but overall errors decreased as net speed increased (r = -0.380). Decreases in net and gross speeds were correlated with increases in time load, mental effort load, stress load, and overall workload (*r*-values from -0.271 to -0.611). Overall typing errors were not significantly correlated with any of the SWAT measures.

SWAT Ratings

All three SWAT measures and the resulting total perceived workload were positively correlated with each other (*r*-values from 0.532 to 0.911).

Discussion

The hypotheses incorporated into the psychosocial factors model were partially validated (Figure 25). Overall, gender, perceived stress (PSS), and locus of control (LOC) did not significantly affect physical outcomes or perceived workload. Mental workload did lead to higher key strike forces for three of six dependent variables considered, and time pressure led to overall higher key strike forces and higher muscle activation. These psychosocial factors increased physical stressors already present in typing activity such as repetitive motions and could theoretically lead to more stress responses. Neither factor had a significant impact on wrist posture. However, both factors increased perceived workload, which may lead to increased stress responses.

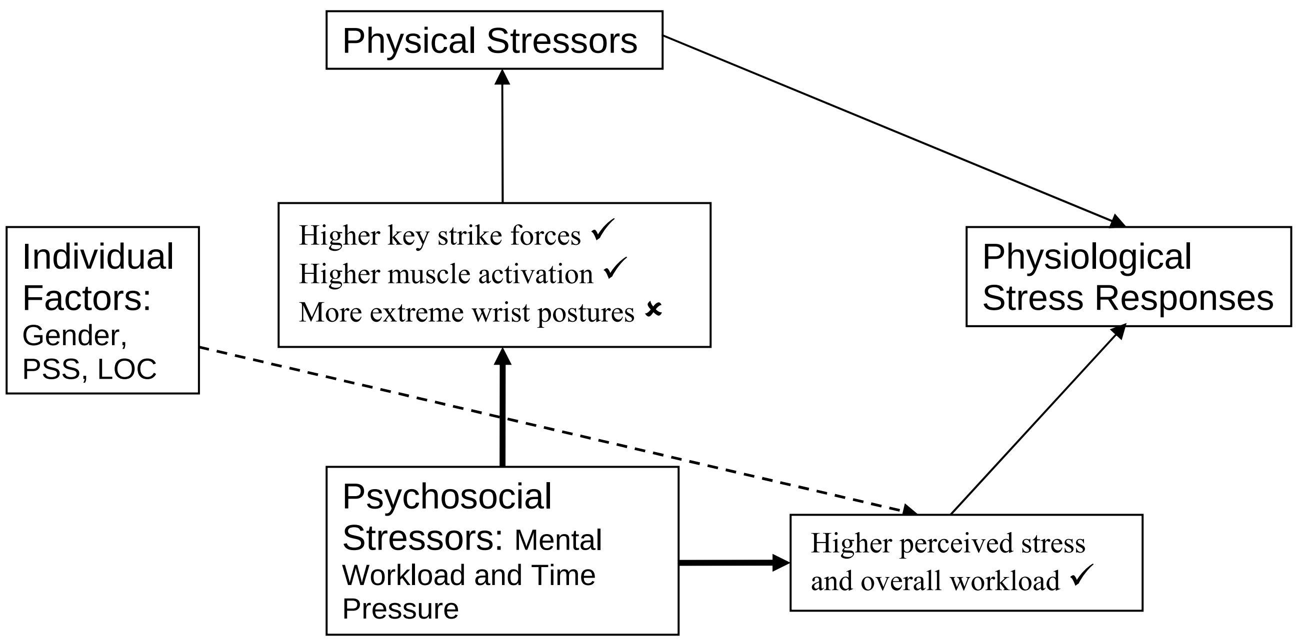

Figure 25. Outcomes of mental workload and time pressure in the psychosocial factors model. (The dashed arrow indicates there was no significant relationship found.)

As hypothesized, time pressure did increase the levels of time load and overall workload perceived by participants, and mental workload increased all measures of perceived workload (time load, mental effort load, stress load, and overall workload). Mental workload was defined by the type of math question and not by the total number of questions attempted by participants, and participants responded to the SWAT scale on perceived workload rather than by their actual performance in typing or answering math questions. This allowed for variation in participants' math and typing abilities.

Typing performance decreased as levels of time pressure and mental workload increased. The decrease in typing performance with additional mental tasks has been observed in a similar study (Leyman et al., 2001). Dual tasks (typing and answering questions) and increased time pressures forced participants to allocate limited mental resources in a speed/accuracy trade-off. Even though gross speed and net speed decreased when mental workload increased, overall errors remained unchanged. However, when participants attempted to type faster, gross speed did increase, but typing errors and net typing speed decreased, although only typing errors were significantly different. Time pressure did not affect the number of math questions answered correctly or the number of math errors. When typing performance decreased, perceived workload (including stress load) increased. Stress can cause cognitive tunneling and working memory loss, which may have reduced performance further (Wickens & Hollands, 2000).

Other studies provide conflicting results in relation to muscle activity changes in the presence of time pressure, additional mental workload, and other psychosocial factors. Increased time pressure did increase muscle activity in the current study, which has been found in another experiment studying finger flexor muscles (Gerard et al., 2002). Mental workload in the current study, however, resulted in decreased muscle activity. This surprising outcome may be related directly to the decrease in typing speed that was associated with the presence of addition or multiplication questions. Correlations revealed that typing speeds were positively associated with muscle activity. Therefore, when math questions were presented, typing speed decreased, and muscle activity also decreased. The decrease in muscle activity with additional mental workload was contrary to findings in several other studies which examined the trapezius and lower arm muscles (including the right ECU) during tasks involving typing or data entry and additional mental tasks (Laursen, Jensen, & Garde, 2002; Leyman et al., 2001; McLean & Urquhart, 2002). Conversely, a recent article studying the effects of psychosocial factors on the trapezius muscle during data entry showed no differences in muscle activity (Blangsted, Sogaard, Christensen, & Sjogaard, 2004). Using the model of multiple resource theory (Wickens & Hollands, 2000), limited mental resources may have forced a decrease in motor response in typing because answering math questions also requires a motor response. Additionally, the discrepancy may lie in the use of the muscles being studied in the experimental task. The current study examined the muscles used directly to complete the typing task, whereas previous studies examined muscles peripheral to the task. The activity of the muscles whose main purpose is support the weight of the arm would not be as directly linked to the physical nature of the task as those muscles studied in the current research.

Decreases in EMG gaps were associated with increases in key strike forces and wrist deviations, which illustrated the interrelationship of previously established physical risk factors of static muscle activation and repetitive motions (NIOSH, 1997). Increases in typing speed can be linked directly to the number of key strikes and wrist deviations (repetitive motions). For this study, wrist deviations were correlated with increases in muscle activity and were negatively correlated with EMG gaps (static muscle activation).

Key strike forces were most affected by time pressure and were significantly correlated with perceived time load and overall workload. Key strike forces were hypothesized to increase as mental workload and perceived stress increased, yet the results for mental workload effects on key strike force remained inconclusive. At this time no other studies have been found that examined key strike forces with mental workload. Time pressure increases resulted in increases in key strike forces and the total number of key strikes, which supported the results found by Gerard et al. (2002). Perceived time load and overall workload were associated with increases in three of the six key strike force measures. Trials with higher mental workload had higher perceived time load and overall workload and were associated with higher key strike forces. Key strike forces were significantly higher when addition questions were answered than the control condition for three key strike force measures but showed no differences for the remaining three measures. Interestingly, slower typing speeds were associated with higher key strike forces, which may be partially explained by decreases in typing performance in the low and high conditions of mental workload. Since typing speed alone is not associated with key strike force, but measures of perceived workload are associated positively with key strike force, key strike force may be more affected by subjective factors than by the physical demands of typing.

Discussion

Mental workload and time pressure did not appear to directly affect wrist deviations or wrist posture, which was contrary to original hypotheses. The number of deviations can be explained most clearly by changes in typing speed. Deviations and gross typing speed decrease significantly with mental workload increases, but both measures increase significantly as time pressure increases. This observation explains the interaction effect of mental workload and time pressure on wrist deviations. Lack of adjustability in the workstation may explain the fixed wrist posture. Participants were not allowed to adjust the tilt of the keyboard or chair height once the experimental trials began, which forced them to remain at approximately the same posture for the duration of testing.

In previous epidemiological studies, individual factors explain only a small percentage of variance in WMSD risk (Faucett & Werner, 1999). Likewise, the current study found no differences for gender, PSS ratings, or LOC ranking. The results support other studies that have found that gender is not a risk factor when males and females perform identical tasks (Malchaire et al., 2001). PSS and LOC rankings may truly have no effect on the factors studied, but lack of significance in PSS and LOC ratings may be due also to the lack of variability in the individuals studied, since all were college students. However, there is evidence that other individual factors, such as personality type, may affect WMSD risk (Glasscock, Turville, Joines, & Mirka, 1999; Skov, Borg, & Orhede, 1996), though these were not investigated in this research.

Conclusions

Limitations

Time pressure and mental workload were not independent of each other, which was reflected by the overlap in ratings of perceived time load in trials with increased mental workload. Although not statistically significant, time pressure increased mental effort load ($p = 0.0781$). Typing faster required more concentration and can be viewed as additional mental workload, and performing the additional task of answering math questions placed more demands on individuals' time allocation strategies. Therefore, it is difficult to conclude that physiological reactions are due solely to time pressure or mental workload.

In general there were few differences between the low and high mental workload level that may have inadvertently reduced the experiment to studying the effects of the presence or absence of additional mental tasks rather than looking at two levels of additional mental workload. Contrary to the hypothesis, several participants mentioned that addition was actually more difficult because their answers were not memorized or rehearsed as well as multiplication. The ability to identify physiological responses at different levels of mental workload and time pressure is needed to determine the level at which adverse reactions begin to occur.

Noise inherent in the recording equipment for EMG signals, key strike forces, and wrist postures could potentially mask the signals of interest, even though precautionary measures (reducing skin impedence, stabilizing lead wires, taping endblocks, etc.) were taken, and filtering algorithms were used in processing the data. Crosstalk between muscles could cause additional noise in EMG signals. While the ECU and FCU are used extensively in typing, finger flexors and extensors are also used. These muscles are located close by in the forearm, and activity from them could be sensed by the electrodes. Drift and crosstalk are limitations in using electrogoniometers (Buchholz & Wellman, 1997; Hansson, Balogh, Ohlsson, Rylander, & Skerfving, 1996), which may cause errors in wrist posture and deviation measures.

Caution must be exercised in comparing key strike forces to results from other studies. The voltage output of the load cells can be adjusted, and a regression equation must be developed to convert the voltage signals to force values. The correlation coefficients calculated for the equations used in this study were very high (0.9829 and 0.9487 for the 'E' and 'N' key regression equations, respectively) but still have the potential to create some error. Additionally, the placement of the load cells under the keys does not measure the force exerted by the fingers but rather the force felt underneath the keys, which may absorb some pressure. Differences in keyboard design could explain differences in force values between studies. Previous studies have found that individuals use around five times more force than needed to activate keys on a keyboard (Armstrong et al., 1994; Feuerstein et al., 1994; Martin et al., 1996).

PSS and LOC rankings appear to be similar across participants, perhaps because almost all of the participants were college students in the same age group. Several participants completed the study around the time of final exams, which could potentially inflate perceived stress ratings compared to other times of the school year. PSS classifications were based on the experimental sample rather than a standard; therefore, categories of perceived stress may not have been distinctly different. The LOC rankings were skewed given that 15 of 18 participants had an internal locus of control while the remaining three were classified as having "both internal and external LOC." The questions used to determine LOC were not highly reliable; therefore, the scores may not reflect a stable individual trait accurately. There is also the possibility that gender, age, and occupational status biased responses to the PSS and LOC questionnaire items creating a confounding variable (Orhede & Kreiner, 2000).

The experimental setup was standardized between participants (i.e., elbows bent to 90 degrees, keyboard tilted at the same angle for all participants, etc.). However, this may not have been the preferred typing position for many participants, especially for five participants that reported using a laptop keyboard most often. This controlled position may have caused increased physical stress to the forearms and mental stress from not being "comfortable" and in a familiar position. Additionally, the electrodes, lead wires, and electrogoniometer end blocks for EMG and wrist posture recording (seven and six wires were attached to the left and right arms, respectively) could also increase stress.

Conclusions

Several aspects of the experimental setup could also create confounding effects on the results including confusion using the SWAT scale to rate trials, asymmetric transfer of skills, and performance demands for the different trial levels. The time load descriptors of the SWAT scale were confusing to several participants during trials that only required typing (control mental workload level) because of the description, "Interruptions or overlap among activities…." Different interpretations of the descriptors may have created inconsistent time load ratings between participants. Correlations revealed that participants perceived an increase in time load when either mental workload or time pressure increased. Although no trial order effects were found, asymmetric transfer may have occurred as participants adjusted to the demands of the experimental trials. Several participants noted that the first trial, which required both typing and answering math questions, seemed extremely difficult. However, they adjusted to the requirements as the experiment progressed. Asymmetric transfer is another potentially confounding factor that may have skewed the results. Asymmetric transfer is seen in experiments requiring new motor skills (for this study, typing and speaking simultaneously) and in studies when measuring stress even when trial orders are randomized or balanced (Poulton & Edwards, 1979). Performance may have been lower and SWAT ratings may have been higher on the first trial that required typing and answering questions regardless of the speed or type of math question.

Finally, typing at a 20% increased pace while answering math questions simultaneously was nearly impossible for most participants and may have affected motivation to achieve expected levels of performance. Most participants stated that typing 20% faster meant typing "as fast as possible" and therefore may have required complete concentration. Few participants were able to achieve 10% or 20% faster typing speeds when asked to answer math questions concurrently. Participants were forced to make a speed/accuracy tradeoff between typing fast, typing correctly, and answering as many math questions as possible. Upon seeing that meeting all levels of performance was not possible, participants seemed to differ in what task they would "give up." Participants were instructed to type continuously and let the math questions be a secondary task, but some had difficulty doing this. Participants differed in the type of math errors committed. Some chose to extend time by saying "repeat" or pausing while others immediately said "skip" to avoid answering more difficult questions.

The experimental task was intended to simulate time pressure and mental pressure, but the actual tasks of answering single-digit math questions and typing at steady, increased speeds may not be realistic. A more realistic example of time pressure would be rushing to meet a deadline, and additional mental tasks may be things like answering the phone, greeting customers, and answering questions of supervisors or co-workers while trying to complete other tasks. Job performance is contingent on meeting job demands, so pressure at work may be much greater than pressure felt by the participants who volunteered their time for the study.

Future Directions

The present study examined only two of many psychosocial factors and could be expanded in several ways. Other factors such as social support from colleagues and supervisors have also been hypothesized to affect WMSD development but were not investigated in this study. It may be that the combination of several psychosocial factors causes more pronounced effects on physiological outcomes than any single factor alone. Therefore, future research should investigate additional psychosocial factors such as management style, level of control over job tasks, and level of support from management and co-workers. It may also be helpful to expand physical outcomes to measures such as heart rate variability and certain hormone levels (Viikari-Juntura & Riihimaki, 1999). Finally, there was little discrimination between the three levels (control, low, and high) of each factor in the current study. It would be helpful to devise an experiment that tests more than two significantly different levels of mental workload and time pressure to determine trends rather than the outcome of the presence or absence of additional mental tasks and time pressures.

As mentioned in the limitations section, the tasks used for this study may not accurately represent tasks performed in the workplace. Field studies that compare muscle activity, awkward postures, and forceful movements with mental workload levels and other psychosocial factors could provide support for laboratory studies. Past studies have utilized questionnaires and medical data to examine psychosocial factors and self-reported physical stressors (e.g. Devereux, Vlachonikolis, & Buckle, 2002), so it is currently difficult to link real-time physical activity and interactions in the working environment with retrospective ratings of psychosocial factors.

Studies with methods that integrate physical measurements with subjective data on the working environment are needed to help determine relationships between physical risk factors and psychosocial factors.

Contributions

Previous studies have examined psychosocial factors of increased mental workload and time pressure while typing on various upper extremity muscles such as the trapezius and extensor digitorum, but this study was the first to examine the ECU and FCU muscles together, which are directly involved in typing. Additionally, many previous studies on psychosocial factors were epidemiological, which limited researchers' abilities to draw causal conclusions. The potential interactions and correlations between muscle activity, key strike forces, and wrist postures were studied in the interest of determining how psychosocial factors affected these established physical risk factors.

The current study provides evidence that increases in time pressure led to increases in lower arm muscle activation, key strike forces, and wrist deviations. Evidence for effects of mental workload on physiological outcomes is weaker due to the potential confounding effect of typing speed, but key strike forces may increase with higher mental workload. For both mental workload and time pressure increases, typing performance decreases and perceived workload (time load, mental effort load, and stress load) increases. These psychosocial factors mediate, or contribute to, physical risk factors which in turn increase overall risk for WMSDs of the upper extremities while typing. Physiological outcomes of muscle activity and wrist deviations appear to be most influenced by the physical demands of typing, but the addition of time pressure and mental demands intensifies the outcomes. Time pressure appears to increase muscle activity and deviations, and mental workload appears to increase key strike forces. However, mental pressure appears to decrease muscle activity, perhaps because other muscles used in typing were not monitored. Therefore, implications for WMSD risk become more complicated to predict since it is the combination of risk factors that most influence risk (NIOSH, 1997)

Several general recommendations can be made based on the current study for any jobs involving hand-intensive work. Performance decreases (total errors increase), and muscle activity, forceful exertions (key strike forces), and repetitive motions (wrist deviations) increase with the addition of time pressure. Therefore, self-paced work may increase productivity and reduce WMSD risk. This translates to having more control over task scheduling in office environments and using human-paced rather than machine-paced assembly lines in manufacturing facilities. High levels of mental workload also decrease performance (decrease typing speed) and may increase forceful exertions and perceived stress and workload. Creating work environments that are conducive to concentration (i.e. limited unnecessary interruptions from co-workers or customers) may reduce feelings of stress and physical risk factors for WMSDs in addition to increasing productivity. In designing jobs and work tasks, both physical and non-physical aspects of the working environment should be considered to provide a workplace that increases productivity and minimizes the risk for WMSD development.

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Appendix A: Informed Consent Form

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

Project Title: Effects of Mental Workload and Time Pressure on the Lower Arm During a Typing Task

Investigator: Laura E. Hughes (Advisor: Dr. Babski-Reeves)

Purpose
This study is designed to examine the effects of time pressure and workload on forearm muscle activity, wrist posture, key activation force, and performance while typing on a standard keyboard. The results of the study will have implications for predicting work conditions that increase the risk of development of work-related musculoskeletal disorders of the upper extremities such as carpal tunnel syndrome.

Procedures
This study will last approximately 2.5 hours. Initially, you will be given a verbal description of the study and its objectives, and you will be asked to read and complete informed consent documents approved through the Institutional Review Board for research involving human participants. You will then be asked to complete a demographic questionnaire, which includes items on previous history or current presence of hand or wrist injuries or illnesses. If you have any condition, past or present, that may affect hand or wrist mobility, you will be excused from the study.

If you meet all inclusion criteria, you will be asked to sit at the experimental computer workstation, which will be adjusted so that the forearms are parallel to the floor, and elbows are at roughly 90°. Chair height will be adjusted so that the knees form a 90^{o} angle and the feet are flat on the floor (when necessary, a foot rest will be used).

You will be screened for typing speed (between 40 and 70 net words per minute using the 10-digit touch method) by completing two 3-minute typing tests. You will complete a typing pretest using SkillCheck software to determine your average typing speed. You will type at a normal, comfortable pace for two sessions of 3 minutes each. If your average speed is less than 40 words per minute or greater than 70 words per minute, or if you do not use the 10-digit touch method of typing, you will be excused from the study.

Electromyography (EMG) surface electrodes (10mm, Ag/AgCl pregelled bipolar electrodes) will be fastened to both forearms over the extensor and flexor carpi ulnaris (ECU and FCU) muscles. These electrodes will cause you no harm, but the area of your arm on which the electrodes will be placed may need to be shaved, slightly abraded, and cleansed with alcohol to ensure good readings for all muscle activity.

During a 15-minute stabilization period, instructions and practice for the experimental trials procedures will be given, and you will be asked to complete a questionnaire on perceived stress. The electrogoniometer will also be attached to your hands and forearms. The electrogoniometer endblocks will be placed on your right and left hands with the arm resting at the side, elbow flexed at 90°, and the forearm and hand lying flat on a table. A straight line will be drawn from the third metacarpophalangeal joint starting along the third metacarpal segment (the bone of the third finger) though the wrist joint and out to mid-forearm. The distal end block of the electrogoniometer will then be centered over the drawn line and attached using double-sided tape. You will then be asked to flex your hand using assistance from the investigator, and the proximal end block of the device will be centered on the line drawn on the superior aspect of the forearm and attached to the wrist as close as possible without distorting the goniometer wire using double-sided tape. To avoid movement of the end blocks, adhesive tape will be placed over each end block.

Following calibration of the equipment (setting of zero angles—neutral position of the wrist) and the 15-minute stabilization period, resting and maximum voluntary exertion (MVE) EMG data will be collected. Resting EMG data will be collected for a 5-second period while your forearms are resting on a table. MVE for both the ECU and FCU will require the performance of three, 5-second palmar extension exertions, each separated by a 45-second rest period. Separate exercises will be performed for the right and left arms.

The main task will consist of typing passages presented through SkillCheck software. This software records typing speed and errors automatically. You may be asked to type at different speeds, or you may be asked to complete math problems orally while typing. The investigator will instruct you on the speed to type and in how to complete any math problems. You will type for 5 minutes in each trial, and there will be a total of 9 trials. You will rest for 3 minutes between each trial. During the rest period, you will be asked to answer several questions to rate workload and stress of the trial. If you have any questions, feel free to ask the investigator before the trials or during the rest periods. At the end of the 9 trials the endblocks and electrodes will be removed, and you will be debriefed.

Risks and Benefits

There is not more than minimal risk associated with this study that would not be found in daily office activities. Temporary discomfort or fatigue in the hands, wrists, and/or forearms may result from typing continuously for 5-minute periods; however, you are encouraged to discontinue usage of the equipment if you experience extreme discomfort. By participating in this study, you will be assisting the investigators in possibly identifying factors that may contribute to the development of work-related musculoskeletal disorders in the hands, wrists and forearms associated with keyboard usage.

Extent of Anonymity and Confidentiality

Your anonymity will be kept in the strictest of confidence. No names will appear on questionnaires or surveys, and a coding system will be used to associate your identity with questionnaire answers and data. All information will be collected in a file and locked when not being used. No videotaping or audiotaping will occur during the experiment.

Informed Consent
You will receive two informed consent forms to be signed before beginning the experiment; one copy will be for your records and the other copy will be obtained for the investigator's records.

Compensation
You will be compensated at a rate of $8 per hour for your participation.

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

Approval of Research
The Department of Industrial and Systems Engineering has approved this research, as required, by the Institutional Review Board (IRB) for Research Involving Human Participants at Virginia Polytechnic Institute and State University.

Participant's Responsibilities
I voluntarily agree to participate in this study. I have the following responsibilities:

1. To read and understand all instructions
2. To answer questions, surveys, etc. honestly and to the best of my ability
3. To type at the speed defined by the investigator to the best of my ability, and to answer any math questions as quickly and accurately as possible for each of the experimental conditions
4. To inform the investigator of any discomforts I experience immediately
5. Be aware that I am free to ask questions at any point

Participant's Permission
I have read and understand the Informed Consent and conditions of this research project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I reserve the right to withdraw at any time without penalty. I agree to abide by the rules of this project.

____

Participant's Signature Date

____

Experimenter's Signature Date

Signature Page

I have read the description of this study and understand the nature of the research and my rights as a participant. I hereby consent to participate with the understanding that I may discontinue participation at any time if I choose to do so.

Participant's Signature   Date

Printed Name

Experimenter's Signature   Date

The research team for this experiment includes Dr. Babski-Reeves and Laura Hughes. Team members may be contacted at the following address and phone number:

Dr. Babski-Reeves
Grado Department of Industrial and Systems Engineering
250 Durham Hall
Blacksburg, VA 24061
540.231.9093

Laura Hughes
Grado Department of Industrial and Systems Engineering
559 Whittemore Hall
Blacksburg, VA 24061
540.230.1033 (h)

In addition, if you have any detailed questions regarding your rights as participant in University Research, you may contact the following individual:

Dr. David Moore
IRB Chair
Assistant Vice Provost Research Compliance
Director, Animal Resources
CMV Phase II
Virginia Tech (0442)
Blacksburg, VA 24061
(540) 231-9359

Appendix B: Demographic Questionnaire

Demographic Questionnaire Participant # _________

Instructions: Please answer the following questions. You may skip any questions you do not wish to answer.

1. Age: _____

2. Gender: _____ Male _____ Female

3. Dominant Hand: _____ Right _____ Left

4. Ethnicity:
_____ Caucasian (European-American)
_____ African-American (Black)
_____ Hispanic/Latino
_____ Asian-American
_____ Other (Please specify: ___________________________)

5. Are you a native English speaker? (Is English your first language?) _____ Yes _____ No

6. Have you ever been diagnosed by a physician with any of the following conditions:

_____ Diabetes _____ Arthritis of the hand or wrist _____ Hypothyroidism

7. Do you have any condition that limits the mobility of your wrist, hand, or fingers? (Note: if you are currently pregnant or have recently experienced rapid weight gain, please mark "yes")

_____ Yes _____ No

If yes, please specify: ____

8. Have you ever broken your hand or wrist? _____ Yes _____ No

9. Have you, in the past 12 months, ever experienced any pain, numbness, or tingling in your wrists, hands, or fingers?

_____ Yes _____ No

10. Are you experiencing any pain, numbness, or tingling in your wrist, hand, or fingers TODAY?

_____ Yes _____ No

11. What type of typing style do you use most often?

____ touch-type with 10 fingers ____ do not touch type/do not type with all 10 fingers

12. How many hours per day do you spend using a computer? _____ hours

Of this time, please give an estimate of the percentage of time spent typing (rather than using the mouse or reading the screen.) Mark on the scale with a vertical line.

0% 25% 50% 75% 100%

|--------------------|--------------------|--------------------|--------------------|

13. What type of keyboard do you use most often?

_____ Standard keyboard _____ "Natural" or split key keyboard _____ Laptop

_____ Other type of keyboard (Please explain):______________________________________

Appendix C: Personal Perceptions Questionnaire

Personal Perceptions

Directions: Respond to each question as quickly as possible. Your first response is likely to be the most accurate depiction of you. For each question, circle the phrase that corresponds best to you.

1. I usually get what I want in life.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

2. I need to be kept informed about news events.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

3. In the last month, how often have you been upset because of something that happened unexpectedly?

Never	Almost Never	Sometimes	Fairly Often	Very Often

4. Other people usually control my life.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

5. I never know where I stand with other people.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

6. In the last month, how often have you felt that you were unable to control the important things in your life?

Never	Almost Never	Sometimes	Fairly Often	Very Often

7. I do not really believe in luck or chance.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

8. In the last month, how often have you felt nervous and “stressed”?

Never	Almost Never	Sometimes	Fairly Often	Very Often

9. I think that I could easily win the lottery.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

10. In the last month, how often have you dealt successfully with irritating life hassles?

Never	Almost Never	Sometimes	Fairly Often	Very Often

11. If I do not succeed on a task, I tend to give up.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

12. In the last month, how often have you felt that you were effectively coping with important changes that were occurring in your life?

Never	Almost Never	Sometimes	Fairly Often	Very Often

13. I usually convince others to do things my way.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

14. In the last month, how often have you felt confident about your ability to handle your personal problems?

Never	Almost Never	Sometimes	Fairly Often	Very Often

15. It is difficult to know who my real friends are.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

16. People make a difference in controlling crime.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

17. In the last month, how often have you found that you could not cope with all the things that you had to do?

Never	Almost Never	Sometimes	Fairly Often	Very Often

18. The success I have is largely a matter of chance.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

19. In the last month, how often have you found that things were going your way?

Never	Almost Never	Sometimes	Fairly Often	Very Often

20. Persistence and hard work usually lead to success.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

21. Marriage is largely a gamble for most people.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

22. In the last month, how often have you been able to control irritations in your life?

Never	Almost Never	Sometimes	Fairly Often	Very Often

23. People must be the master of their own fate.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

24. In the last month, how often have you felt that you were on top of things?

Never	Almost Never	Sometimes	Fairly Often	Very Often

25. It is not important for me to vote.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

26. Leaders are successful when they work hard.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

27. In the last month, how often have you been angered because of things that happened that were outside of your control?

Never	Almost Never	Sometimes	Fairly Often	Very Often

28. My life seems like a series of random events.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

29. In the last month, how often have you found yourself thinking about things that you have to accomplish?

Never	Almost Never	Sometimes	Fairly Often	Very Often

30. I never try anything that I am not sure of.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

31. In the last month, how often have you been able to control the way you spend your time?

Never	Almost Never	Sometimes	Fairly Often	Very Often

32. I earn the respect and honors I receive.

Disagree Very Much	Disagree Moderately	Disagree Slightly	Agree Slightly	Agree Moderately	Agree Very Much

33. In the last month, how often have you felt difficulties were piling up so high that you could not overcome them?

Never | Almost Never | Sometimes | Fairly Often | Very Often

34. A person can get rich by taking risks.

Disagree Very Much | Disagree Moderately | Disagree Slightly | Agree Slightly | Agree Moderately | Agree Very Much

Scoring Details

Perceived Stress Scale (PSS)

PSS ratings are measured using items 3, 6, 8, 10, 12, 14, 17, 19, 22, 24, 27, 29, 31, and 33, which are scored on a scale of 1 to 5 from "Never" to "Fairly Often." Items 10, 12, 14, 19, 22, 24, and 31 are reverse-scored. Participants obtain an overall score between 14 and 70 with higher numbers indicating an increased level of perceived stress.

Locus of Control (LOC)

LOC is measured using items 1, 2, 4, 5, 7, 9, 11, 13, 15, 16, 18, 20, 21, 23, 25, 26, 28, 30, 32, and 34, which are scored on a scale of 0 to 5 from "Disagree Very Much" to "Agree Very Much." Items 4, 5, 9, 11, 15, 18, 21, 25, 28, and 34 are reverse-scored. Overall scores range from 0 to 100 and are converted to one of the following rankings based on Pettijohn's questionnaire (1998) :

Table 8. LOC rankings.

Total Score	Degree of External/Internal LOC
0-20	Very strong external LOC
21-40	External LOC
41-60	Both external and internal LOC
61-80	Internal LOC
81-100	Very strong internal LOC

Appendix D: Subjective Workload Assessment Technique (SWAT) (Not to scale)

Form D

Participant # _____

Trial # _____

Time Load, Mental Effort Load, and Stress Load Ratings

Often have spare time. Interruptions or overlap among activities occur infrequently or not at all.	Occasionally have spare time. Interruptions or overlap among activities occur frequently.	Almost never have spare time Interruptions or overlap among activities are very frequent, or occur all the time.
Very little conscious mental effort or concentration required. Activity is almost automatic, requiring little or no attention.	Moderate conscious mental effort or concentration required. Complexity of activity is moderately high due to uncertainty, unpredictability, or unfamiliarity. Considerable attention required.	Extensive mental effort and concentration are necessary. Very complex activity requiring total attention.
Little confusion, risk, frustration, or anxiety exists and can be easily accommodated.	Moderate stress due to confusion, frustration, or anxiety noticeably adds to workload. Significant compensation is required to maintain adequate performance.	High to very intense stress due to confusion, frustration, or anxiety. High to extreme determination and self-control required.

Appendix E: Demographic Summary of Participants

Demographic Variable	Count or Mean (standard deviation)
Gender	9 Females
	9 Males
Age	25.4 (6.4)
Dominant Hand	17 Right
	1 Left
Ethnicity	8 Caucasian
	5 Asian-American
	4 African-American
	1 Other: Asian
First Language	14 Native English speakers
	4 Non-native English speakers
Report of pain, numbness, or tingling in hands or wrists in past 12 months	16 no
	2 yes
Hours spent using a computer per day	4.6 (2.5)
Percentage of time spent typing	38% (21%)
Hours spent typing per day	1.7 (1.4)
Keyboard type used most often	13 Standard
	5 Laptop
Average net typing speed (words per minute)	52.8 (7.5)
Perceived Stress Scale Rankings	6 Low
	7 Medium
	5 High
Locus of Control (LOC) Rankings	15 Internal LOC
	3 Both Internal and External LOC

Appendix F: P-values for Normality Test (Shapiro-Wilk's)

(Highlighted values indicate non-normal data.)

Dependent variables	Control, Control*	Control, Low	Control, High	Low, Control	Low, Low	Low, High	High, Control	High, Low	High, High	% Normal Trials
Right ECU mean	0.1057	0.1678	0.2167	0.1345	0.2594	0.4828	0.2174	0.5409	0.0532	100%
Right FCU mean	0.3303	0.3472	0.5359	0.4093	0.7855	0.3545	0.2363	0.2439	0.3058	100%
Left ECU mean	0.567	0.0105	0.2475	0.1607	0.0026	0.4015	0.0858	0.2054	0.2307	67%
Left FCU mean	0.0067	0.0009	0.1645	0.0166	0.3161	0.6585	0.0006	0.0004	0.0001	33%
Right ECU median	0.1396	0.131	0.1097	0.2448	0.0402	0.3341	0.3265	0.7522	0.1009	89%
Right FCU median	0.236	0.2352	0.3257	0.3017	0.7477	0.2012	0.2117	0.1004	0.3064	100%
Left ECU median	0.6083	0.0053	0.2482	0.2088	0.0622	0.1504	0.0559	0.1985	0.3152	89%
Left FCU median	0.0027	0.0019	0.9855	0.0162	0.2623	0.6386	0.0004	0.0002	<0.0001	33%
Right ECU gaps	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0%
Right FCU gaps	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0%
Left ECU gaps	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	NA	<0.0001	0%
Left FCU gaps	<0.0001	0.0009	0.0003	<0.0001	<0.0001	0.0002	0.0004	<0.0001	0.0022	0%
E key mean force	0.4521	0.5786	0.2635	0.9406	0.5285	0.6726	0.8924	0.7741	0.527	100%
N key mean force	0.6437	0.8694	0.8441	0.292	0.8579	0.9117	0.3738	0.9301	0.9167	100%
E key median force	0.4027	0.4511	0.2401	0.8453	0.387	0.5196	0.8842	0.9154	0.623	100%
N key median force	0.6477	0.5899	0.9374	0.6047	0.7532	0.8484	0.1849	0.8959	0.8377	100%
E key maximum force	0.6188	0.9049	0.7467	0.2355	0.8053	0.0733	0.6772	0.9606	0.3269	100%
N key maximum force	0.9753	0.635	0.5333	0.0534	0.3062	0.7096	0.6051	0.9997	0.1682	100%
E key strikes (total)	0.7336	0.0004	0.0172	0.949	0.3405	0.0095	0.5177	<0.0001	0.0005	44%
N key strikes (total)	0.0211	0.5841	0.0971	0.5971	0.4534	0.0014	0.6895	0.0019	0.0068	56%
Right RU mean	0.7272	0.4844	0.4105	0.5468	0.0575	0.8392	0.0594	0.4496	0.953	100%
Right FE mean	0.2955	0.3172	0.1358	0.0194	0.4584	0.041	0.9974	0.076	0.4499	78%
Left RU mean	0.0466	0.3981	0.134	0.105	0.3929	0.117	0.9164	0.3919	0.0352	78%
Left FE mean	0.4947	0.8274	0.8506	0.1081	0.4383	0.9591	0.724	0.8312	0.3713	100%
Right RU median	0.7374	0.442	0.4647	0.537	0.0733	0.8102	0.0534	0.4276	0.8773	100%
Right FE median	0.2471	0.3214	0.112	0.0198	0.5618	0.0462	0.9864	0.0887	0.3927	78%
Left RU median	0.055	0.3395	0.1205	0.091	0.4097	0.1273	0.9465	0.38	0.0272	89%
Left FE median	0.57	0.7199	0.7984	0.1133	0.6202	0.9702	0.7146	0.5742	0.3293	100%
Right RU deviations	0.3637	0.1094	0.2178	0.1768	0.0814	0.1695	0.0821	0.149	0.0265	89%
Right FE deviations	0.2377	0.0141	0.0379	0.1531	0.0293	0.0173	0.175	0.0078	0.0635	44%
Left FU deviations	0.0009	0.0119	0.0346	0.0377	0.1125	0.0145	0.0326	0.009	0.0459	11%
Left FE deviations	0.0927	0.0847	0.3219	0.0268	0.1005	0.5167	0.5371	0.2322	0.0864	89%
Gross speed	0.0486	0.0161	0.0201	0.7628	0.3059	0.0926	0.1078	0.024	0.0408	44%
Net speed	0.7642	0.4867	0.3509	0.4341	0.117	0.9116	0.8621	0.0403	0.3015	89%
Overall typing errors	0.2742	0.0305	0.0242	0.2778	0.0007	0.0056	0.728	0.0004	0.0008	33%
Missing words	0.2	0.22	0.1351	0.0921	0.0174	0.1118	0.0219	0.0005	0.0268	56%
Extra words	<0.0001	0.0003	<0.0001	<0.0001	0.0026	<0.0001	<0.0001	<0.0001	0.0017	0%
Joined words	0.0002	<0.0001	0.0005	<0.0001	<0.0001	0.0003	0.0002	<0.0001	<0.0001	0%
Splits words	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0002	<0.0001	0%
Misspelled words	0.2935	0.0218	0.0032	0.2079	0.0002	0.0062	0.7782	0.0007	0.0004	33%

**Trial combinations denoted by (time pressure level, mental workload level)*

(cont.)

Dependent variables	Control, Control	Control, Low	Control, High	Low, Control	Low, Low	Low, High	High, Control	High, Low	High, High	% Normal Trials
No response (math)	NA	<0.0001	<0.0001	NA	<0.0001	<0.0001	NA	<0.0001	<0.0001	0%
Repeat (math)	NA	0.0106	0.0007	NA	0.0005	0.0002	NA	<0.0001	0.0012	0%
Skip (math)	NA	<0.0001	<0.0001	NA	<0.0001	<0.0001	NA	<0.0001	<0.0001	0%
Wrong (math)	NA	0.0016	0.202	NA	0.0037	0.0058	NA	0.0511	0.0024	33%
Total math errors	NA	0.0855	0.0053	NA	0.109	0.0906	NA	0.2236	0.4415	83%
Correct (math)	NA	0.2209	0.2254	NA	0.3521	0.3273	NA	0.935	0.8996	100%
Time load	0.1386	0.0493	0.06	0.811	0.0036	0.0192	0.0922	0.0038	0.0004	44%
Mental effort load	0.4088	0.1875	0.0636	0.9796	0.0886	0.06	0.3709	0.1764	0.0009	89%
Stress load	0.0084	0.9035	0.5964	0.4528	0.661	0.4752	0.1147	0.6187	0.1234	89%
Overall workload	0.2457	0.5254	0.1275	0.9389	0.1752	0.7963	0.6718	0.2275	0.0173	89%

Appendix G: Tukey HSD Results

Significant Differences for Mental Workload Levels
(Means with the same letter are not significantly different.)

Variable	Mental Workload Level	Mean	Significant Difference	Variable	Mental Workload Level	Mean	Significant Difference
Right ECU	control	0.154455	A	Left RU	control	11.3678	A
mean	low	0.138559	B	mean	high	10.2271	A B
	high	0.135137	B		low	9.2373	B
Right FCU	control	0.076784	A	Left RU	control	10.8892	A
mean	low	0.068248	B	median	high	9.73	A B
	high	0.065823	B		low	8.7925	B
Left FCU	control	0.084362	A	Right RU	control	451.926	A
mean	low	0.07495	B	deviations	low	418.241	B
	high	0.070194	B		high	416.352	B
Right ECU	control	0.137688	A	Right FE	control	1112.93	A
median	low	0.121988	B	deviations	low	1023.43	B
	high	0.117412	B		high	1009.02	B
Right FCU	control	0.066601	A	Left RU	control	479.3	A
median	low	0.055499	B	deviations	low	439.09	B
	high	0.052647	B		high	426.02	B
Left ECU	control	0.127875	A	Left FE	control	1175.13	A
median	low	0.121881	A B	deviations	low	1100.87	B
	high	0.113379	B		high	1054.46	B
Left FCU	control	0.073304	A	Gross	control	66.5981	A
median	low	0.061276	B	Speed	low	56.4574	B
	high	0.055601	B		high	53.8019	C
N key	low	1.78742	A	Net	control	48.843	A
mean	high	1.75924	A B	Speed	low	38.4	B
	control	1.71979	B		high	36.904	B
N key	low	1.78127	A	Time	high	15.6446	A
median	high	1.75358	A B	Load	low	14.6378	A
	control	1.71758	B		control	10.6059	B
E key	low	2.43215	A	Mental Effort	high	15.4602	A
maximum	high	2.3816	A B	Load	low	14.875	A
	control	2.35578	B		control	7.6967	B
E key	control	155.185	A	Stress	high	13.1528	A
strikes	low	134.37	B	Load	low	12.803	A
	high	124.315	C		control	6.1124	B
N key	control	95.833	A	Overall	high	44.258	A
strikes	low	89.167	A	Workload	low	42.316	A
	high	79.185	B		control	24.415	B

Significant Differences for Time Pressure Levels
(Means with the same letter are not significantly different.)

Variable	Time Pressure Level	Mean	Significant Difference
Right FCU	high	0.073194	A
mean	low	0.069574	A B
	control	0.068089	B
Right FCU	high	0.060978	A
median	low	0.057591	A B
	control	0.056177	B
E key	high	1.62799	A
mean	low	1.59717	A B
	control	1.57133	B
N key	high	1.78525	A
mean	low	1.75734	A B
	control	1.72386	B
E key	high	1.644	A
median	low	1.60894	A B
	control	1.57829	B
N key	high	1.78864	A
median	low	1.75034	A B
	control	1.71344	B
E key	high	2.44163	A
maximum	low	2.3867	A B
	control	2.3412	B
E key	high	143.13	A
strikes	low	139.167	A B
	control	131.574	B
Right FE	high	1090.41	A
deviations	control	1031.15	B
	low	1023.81	B
Left FE	high	1150.54	A
deviations	low	1109.43	A B
	control	1070.5	B
Gross	high	60.1907	A
Speed	low	58.8148	A B
	control	57.8519	B
Overall	high	33.87	A
Typing Errors	low	28.741	B
	control	26.167	B
Time	high	14.5456	A
Load	low	14.3057	A
	control	12.037	B
Overall	high	38.822	A
Workload	low	38.384	A
	control	33.783	B

Appendix H: Math Performance t-tests

Correct Responses

Test for Equality of Variance
H_o: Variances for correct addition and multiplication responses are equal.
H_a: Variances for correct addition and multiplication responses are not equal.
$\alpha = 0.05$
$p = 0.1042$
The null hypothesis is not rejected, therefore assume variances are equal. A paired t-test will be used to test for differences between the number of addition and multiplication questions answered correctly.

Test to Compare Correct Addition and Multiplication Responses
H_o: Number of correct addition < Number of correct multiplication
H_a: Number of correct addition > Number of correct multiplication
$\alpha = 0.05$

Time pressure level	**p-value**
Overall	<0.0001
Control	0.0002
Low	0.0158
High	<0.0001

The null hypothesis is rejected for all 4 cases: the number of correct addition responses is greater than the number of correct multiplication responses.

Total Math Errors

Test for Equality of Variance
H_o: Variances for total addition and multiplication errors are equal.
H_a: Variances for total addition and multiplication errors are not equal.
$\alpha = 0.05$
$p = 0.0002$
The null hypothesis is rejected; therefore assume variances are not equal. A t-test with unpooled variance terms will be used to test for differences between total addition and multiplication errors.

Test to Compare Total Addition and Multiplication Errors
H_o: Total addition errors > Total multiplication errors
H_a: Total addition errors < Total multiplication errors
$\alpha = 0.05$

Time pressure level	**p-value**
Overall	<0.0001
Control	0.0141
Low	0.1202
High	0.0017

The null hypothesis is rejected except for one case: total addition errors are statistically less than total multiplication errors except in the low time pressure condition.

Vita

Laura Hughes graduated Summa Cum Laude as a valedictorian from North Carolina State University with a Bachelor's of Science in Industrial Engineering and a minor in Psychology in May 2002. Additionally as an undergraduate she completed requirements for the University Honors Program and participated in the cooperative education program by working as a management engineer in several hospitals for Premier, Inc. She directly continued her education at Virginia Tech in the Human Factors Option of the Industrial and Systems Engineering Department where she does research in the Industrial Ergonomics Laboratory. She received the National Institute for Occupational and Safety Health Fellowship and the Pratt Fellowship to fund her education. Laura is an active member of the Human Factors and Ergonomics Society (HFES), the American Society of Safety Engineers (ASSE), Phi Kappa Phi, Alpha Pi Mu, and the Institute of Industrial Engineers. She serves as treasurer of both HFES and ASSE. Upon completion of the Master's of Science degree, Laura plans to pursue a PhD in human factors in the area of musculoskeletal disorder prevention.