WRIST BIOMECHANICS AND ULTRASONOGRAPHIC MEASURES OF THE MEDIAN NERVE DURING COMPUTER KEYBOARDING

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Keyboarding is a highly repetitive daily task and has been linked to musculoskeletal disorders of the upper extremity. However, the effect of keyboarding on median nerve injuries is not well understood. The purpose of this study was to determine whether continuous keyboarding can cause acute changes in the median nerve and whether these changes are correlated with wrist biomechanics during keyboarding.

Ultrasound images of the median nerve from forty healthy volunteers were captured at the levels of the pisiform and distal radius prior to and following a prolonged keyboarding task (i.e., one hour of continuous keyboarding). Images were analyzed by a blinded investigator to quantify the median nerve characteristics. Changes in the median nerve ultrasonographic measures as a result of continuous keyboarding task were evaluated and compared to the hand and wrist biomechanical variables, which were collected simultaneously.

Cross-sectional areas at the pisiform level were significantly larger in both dominant and non-dominant hands following the keyboarding task. Swelling ratio was also significantly greater in both hands after 30 and 60 minutes of keyboarding when compared to the baseline measures. Both cross-sectional area and swelling ratio, however, decreased after 30 minutes of manual rest. These acute changes were positively correlated to biomechanical variables of wrist, including wrist flexion and tendon travel.

We were able to detect acute changes in the median nerve ultrasound characteristics following one hour of computer keyboarding. These changes were significantly correlated to the wrist biomechanics. The findings suggest that keyboarding has an impact on the median nerve. Further studies are required to understand this relationship, which would provide insight into the pathophysiology of median neuropathies such as carpal tunnel syndrome.

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PREFACE

First and foremost, I would like to thank my family; especially my wonderful wife, Marjan. My graduate work would not be complete without constant encouragement and support from her, as well as from her family. I would also like to thank my son, Nicholas, and my daughter, Emma, for making my life more meaningful. I dedicate this dissertation to them, because they were the sole reason and main motivation for me to go back to school at age 40.

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1.0 INTRODUCTION

Carpal tunnel syndrome (CTS) is a common, costly public health problem in the United States, with as many as 3 million individuals suffering from its symptoms and complications.[1] It has become one of the fastest growing occupational disorders in the United States, increasing over 60% in data entry/typing positions over the past decade.[2] Treatment is estimated to cost over one billion dollars a year.[3] The incidence of surgical intervention for carpal tunnel syndrome has been reported to be 0.9/1000.[1]

Carpal tunnel is a narrow pathway on the palm side of the wrist. It is bounded at the bottom by the wrist bones, forming a bony groove, and covered by a tough fibrous structure named the flexor retinaculum. This tunnel contains the flexor tendons that bend the fingers and the median nerve, which controls sensation and movement of most parts of the hand (Figure 1).

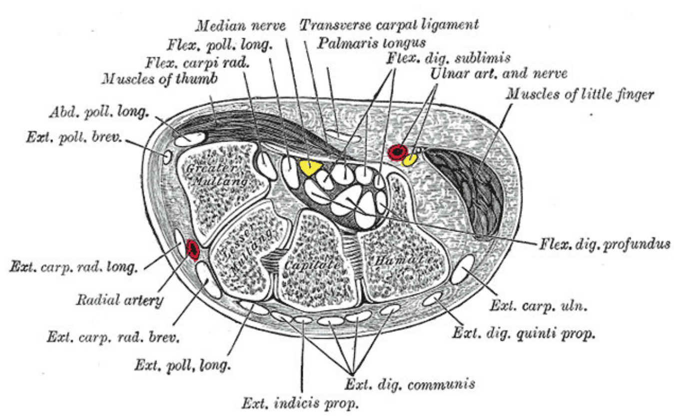


Figure 1. A cross section of the human wrist depicting the carpal tunnel (from Gray's Anatomy)

The median nerve exits the cervical spine from the brachial plexus and runs down the entire length of the arm to the carpal tunnel of the wrist. Compression of the median nerve inside the tunnel can produce symptoms such as numbness, tingling, pain and hand weakness that characterize carpal tunnel syndrome.[4,5] Women are three times more likely to develop carpal tunnel syndrome than men. The risk of carpal tunnel syndrome also increases with age, with the highest risk between 40 and 60 years of age. Certain health conditions can increase the risk, including hypothyroidism, diabetes, obesity and rheumatoid arthritis. Women who are pregnant, taking oral contraceptives or going through menopause also are at increased risk, most likely due to hormonal changes.

1.1 CARPAL TUNNEL SYNDROME

1.1.1 Pathogenesis

The most prevalent and accepted theory for the pathogenesis of carpal tunnel syndrome is compression of median nerve in the carpal tunnel.[4,5] Although this theory is widely accepted, the cause of the compression in the carpal tunnel is not fully understood. Epidemiological research has identified several occupational risk factors associated with the development of carpal tunnel syndrome in general industry, including force, repetition, awkward or static postures, localized mechanical compression, and vibration. Several studies found particularly greater prevalence of carpal tunnel syndrome in workers with highly repetitive manual jobs.[6,7] Loslever, in a study of risk factors for carpal tunnel syndrome in the workplace, found frequency of performing a task to be associated with carpal tunnel syndrome.[2]

In a study of 700 clerical and manufacturing workers, Werner et al. discovered that the 184 active workers with electrodiagnostic evidence of median mononeuropathy performed jobs with a higher level of hand repetition.[8] In looking at motion repetitiveness, Roquelaure et al. studied 130 workers, half of whom had carpal tunnel syndrome, and found factors related to frequency of a task to be more highly correlated with carpal tunnel syndrome than wrist posture or forces.[9] Silverstein et al. performed a biomechanical investigation of a number of jobs and stratified these to determine the risk of carpal tunnel syndrome.[5] The authors reported that high repetition jobs were associated with carpal tunnel syndrome. Jobs rated as being higher force were also related to the risk of carpal tunnel syndrome. Roquelaure used the weight of tools and parts handled to determine forces exerted at the hand.[9] This study found that lifting an object weighing greater than 1 kg in mass was associated with carpal tunnel syndrome (odds ratio = 9.0). Armstrong's study of work related risk factors for carpal tunnel syndrome found individuals with carpal tunnel syndrome used higher forces in all positions than individuals without carpal tunnel syndrome who were performing the same work task.[10]

1.1.2 Musculoskeletal Disorders and Computer Keyboarding

Moore[11], in his review of musculoskeletal disorders of the upper extremity, identified several biomechanical factors postulated to be the pathogenesis for common musculoskeletal disorders. Mechanisms which appear to cause histological changes in the tendons, muscles, and nerves include repetition and/or forceful exertions, which can lead to fatigue and exhaustion in muscle groups. Other possible mechanisms for tissue damage include ischemic caused by compression related occluded blood supply[12] viscoelastic creep responses related to cumulative strain on the tendons; [13] tendon travel and the acceleration of tendon during activity.[14,15]

Keyboarding is a highly repetitive task, and its association with musculoskeletal disorders of the upper extremity has been a public health issue since the mid-1980s.[16] According to the Bureau of Labor Statistics 2004 data, 32% (402,700 cases) of all illnesses and injuries involving days away from work were due to repetitive motion.[17] This data showed that tasks such as keyboarding caused the longest median absences (20 days) from work. Research studies in industrial settings have shown that the incidence of musculoskeletal disorders of the upper extremity relates to the amount of computer use.[18,19] An extensive review of the literature demonstrated that the prevalence of musculoskeletal disorders among keyboard users varied from 9% to 50%, when compared to control groups (low levels of or no keyboard use) where prevalence ranged from 4.5% to 17%.[20] The incidence of computer-related musculoskeletal disorders is a serious concern as the number of people using a computer at work continues to steadily rise. In 1993, 45.8% of all workers used a computer, by 1997 use had risen to 49.8%[21], and by 2003 to 56.1%.[22] A study by Baker et al. found that for age, gender, occupation, and computer use, the greatest risk factor for musculoskeletal disorders of the upper extremity was computer use.[23] In all of these studies, carpal tunnel syndrome was one of the reported musculoskeletal disorders.

1.1.3 Carpal Tunnel Syndrome and Computer Keyboarding

Despite numerous research studies investigating the clinical effects of keyboarding,[24-34] there is still a major controversy with regard to the relationship between carpal tunnel syndrome and computer keyboarding. On the one hand, some researchers demonstrated that there was not sufficient epidemiological evidence to prove such a relationship exists, or that prevalence of CTS among the computer users was similar to the general population.[24-28]

On the other hand, several studies showed up to three times higher prevalence of CTS among computer users than the general population and suggested an association between CTS and computer use. [29-33] In one study, Shafer-Crane et al. utilized magnetic resonance imaging (MRI) to visualize acute changes in the median nerve as a result of continuous keyboarding and found that the median nerve long axis/short axis ratio decreased in subjects without carpal tunnel syndrome symptoms after three hours of typing, while symptomatic subjects demonstrated no significant changes in their median nerves.[34]

1.1.4 Rationale

The controversial results of above-mentioned studies suggest that a better understanding of the median nerve tissue response to continuous keyboarding is required prior to establishing a possible correlation between carpal tunnel syndrome and keyboarding. Pathophysiology of carpal tunnel syndrome is multi-factorial, and although keyboarding is a highly repetitive task that can impose forces and awkward postures on the wrist, it does not encompass all the contributive factors that cause carpal tunnel syndrome.

The presented study investigated acute changes in the median nerve resulting from keyboarding and examined whether those changes correlated to wrist and hand biomechanical variables. This study was a necessary step toward exploring a potential link between keyboarding and pathophysiology of median nerve injury. It is possible that the changes in the median nerve represent normal physiological responses to repetitive use. However, if we can relate specific biomechanics to nerve changes it provides additional evidence of causality. Even in the absence of causality, linking specific biomechanics to tissue response involves a methodology which will likely prove useful in other repetitive tasks.

In addition, linking acute changes and biomechanics provide a means of investigating interventions. Ultimately, the long term goal of such interventions would be to interrupt the development of carpal tunnel syndrome in high-risk population, to preclude the need for surgical treatment, and reduce the excessive number of lost days and financial burden currently due to work-related carpal tunnel syndrome.

1.2 ULTRASONOGRAPHY

1.2.1 Ultrasonography and Musculoskeletal Structure

Ultrasonography is a well-established method for examining soft tissue structures of the musculoskeletal system. Ultrasound is a relatively inexpensive, dynamic, and noninvasive technique, which requires short examination times,[35] and can be used even in non-clinical settings. When viewing structures via ultrasound, those containing more fluid appear hypoechoic, or darker (e.g. nerves, blood vessels), while those containing less fluid appear more hyperechoic, or lighter (e.g. bones, tendons). High frequency transducers allow for the depiction of peripheral nerves and tendons. In fact, ultrasound has been proven to be a very precise method of viewing such musculoskeletal structures. Kamolz et al. measured the cross-sectional areas of the median nerves of 20 cadavers both anatomically and using ultrasonography and found no significant differences between those measurements. They concluded that ultrasound can precisely display the anatomy of the carpal tunnel and median nerve.[36]

Many studies have shown ultrasound to be useful in the diagnosis of carpal tunnel syndrome. Buchberger et al. found that the median nerve of subjects with carpal tunnel syndrome had significantly larger cross-sectional area (CSA) at the pisiform level and flattening ratio (nerve width divided by nerve height) at the hamate level.[37] Other investigators have confirmed these findings, with the most consistent finding being an increased CSA of the median nerve at the pisiform level.[37-47] Other common findings include increased swelling ratio (CSA at pisiform level / CSA at distal radius) and increased palmar bowing of the flexor retinaculum. In summary, larger flatter nerves tend to be more associated with carpal tunnel syndrome than smaller, rounder nerves.

1.2.2 Ultrasonography and Acute Changes of the Median Nerve

A few studies have used ultrasound as a research tool to examine acute changes of the median nerve due to occupational activities.[48,49] Massy-Westropp et al.[49] recruited 40 subjects to participate in a study that examined acute size changes of the median nerve following a 5-minute cutting task. Subjects were asked to maintain a pace of 4 cuts every 5 seconds. The authors reported an increase in median nerve size after the task was completed. Subjects responded differently based on gender and body mass index (BMI). Females exhibited changes immediately after activity and those with a higher BMI experienced more median nerve swelling compared to people with a lower BMI. Altinok et al.[48] studied a case group with carpal tunnel syndrome and a control group without carpal tunnel syndrome symptoms. Twenty wrists were studied in each group. Two exercises were performed to simulate work-related stresses: one simulated wringing laundry and one simulated jar opening and closing. The case group experienced significantly more swelling than the control group due to the two exercise tasks.

Our laboratory has successfully used ultrasound to study changes in the musculoskeletal structures of the upper extremities.[50-54] In particular, ultrasonographic techniques have been used to quantify acute changes in the median nerve following repetitive physical activities.[52] The results of these studies demonstrated that ultrasound is a repeatable research tool to make accurate measurements of the shape and size of the median nerve at various levels of the wrist.[52] Impink et al. showed that ultrasound is a reliable tool for measuring the median nerve and therefore may be useful for assessing acute changes in median nerve measures, and suggested that as long as a standard imaging protocol is followed, in which a single investigator performs the imaging, CSA, FR, and SR are highly reproducible.[54] The results also showed that the nerve could be reliably measured even when no changes have occurred.

1.3 KINEMATICS OF KEYBOARDING

Although there is great variety in preferred postures among different keyboard users,[55-57] research suggests that individual keyboarding kinematics are relatively stable and unchanging during keyboarding tasks.[58,59] The postures assumed do not appear to be necessarily related to the anthropometrics of the keyboard user,[57] but do appear to be related to the physical characteristics of the workstation,[60-67] suggesting that a well-controlled workstation is necessary to minimize introducing unwanted variables. Studies suggest that standard keyboard users maintain their left wrist an average of 66 degrees (± 8.3) pronation, 15 degrees (± 7.7) ulnar deviation, and 21 degrees (± 8.8) extension; and the right wrist at 62 degrees (± 10.6) pronation, 10 degrees (± 7.2) ulnar deviation, and 17 degrees (± 7.4) extension.[57] These postures vary considerably from subject to subject. However, the typical postures assumed may not be the best postures for computer keyboard users. Although pronation has been hypothesized to be a risk factor,[68] little research has been completed to determine the effect of pronation on repetitive strain injury. Ulnar wrist deviations of 20 degrees or more have been associated with repetitive strain injury and increased pain/discomfort.[69]

Epidemiological studies that have examined the relationship between wrist extension and musculoskeletal pain/discomfort have generally not found a significant association between the two.[69-71] This has not prevented researchers from hypothesizing the safe level of wrist posture. Assessment tools have set 15 degrees or less of wrist extension as a safe posture.[72,73] Several researchers have been studying the effect of using a negative pitch keyboard which places the wrist at neutral (0 degrees of extension)[61,63,74,75] and report that this can reduce EMG readings, carpal tunnel pressure, and subjective reports of pain/discomfort.

While research studies provide important information about the basic kinematics of keyboarding, the optimal kinematics for computer keyboarding is not fully known. Ergonomic interventions, such as alternative keyboards, have been shown to be an effective method to reduce awkward postures of the wrist and forearm,[76] although they are less successful in reducing finger and thumb harmful postures,[59] decreasing tendon travel,[77] and reducing mechanical compression of the carpal tunnel area by reducing pronation.[78] A better understanding of median nerve injury is required to design a comprehensive interventional approach.

1.4 HYPOTHESES AND SPECIFIC AIMS

1.4.1 Specific Aim 1

Our first Specific Aim was to identify acute changes in the median nerve at the wrist after a period of keyboarding using ultrasound techniques. We hypothesized that following a continuous keyboarding task the median nerve will exhibit the following changes when compared to baseline images collected prior to keyboarding:

1) A larger cross-sectional area (CSA) at the pisiform level;
2) Increased swelling ratio (CSA at pisiform level / CSA at distal radius);
3) Increased flattening ratio (nerve width divided by nerve height) at the pisiform level.

1.4.2 Specific Aim 2

We measured wrist and hand biomechanical variables and correlated them to acute changes observed in the median nerve due to keyboarding. Our second hypothesis indicated that acute changes in the median nerve as described in the first hypothesis would be positively correlated to the following biomechanical variables collected during keyboarding:

1) Average peak ulnar deviation of the wrist and average peak wrist extension;
2) Average keystroke forces;
3) Typing speed (words per minute);
4) Average peak resultant flexor tendon travel.

2.0 CHAPTER I

ACUTE CHANGES OF THE MEDIAN NERVE AS A RESULT OF PROLONGED KEYBOARDING

2.1 INTRODUCTION

Carpal tunnel syndrome (CTS) is a common, costly problem in the general population and in manual workers.[6,9,16] In the United States of America alone, an estimated 1.6% of adults population self-reported carpal tunnel syndrome, with more than 3 million individuals experiencing its symptoms and signs.[1] In another study, the prevalence of clinically and electrodiagnostically confirmed carpal tunnel syndrome in a general population was reported as 2.7%.[5] Treatment of CTS is estimated to cost over one billion dollars a year. [3]

The most prevalent theory for the pathogenesis of carpal tunnel syndrome is compression of median nerve in the carpal tunnel.[4,5] Although this theory is widely accepted, the cause of the compression in the carpal tunnel is not fully understood. Epidemiological research has identified several occupational risk factors associated with the development of carpal tunnel syndrome in general industry including: force, repetition, awkward/static postures, localized mechanical compression, and vibration.[79-82] Several studies have found a greater prevalence of carpal tunnel syndrome in workers with highly repetitive manual jobs.[6,20,83]

Keyboarding is a highly repetitive daily task, and its association with musculoskeletal disorders of the upper extremity has been a public health concern since the mid-1980s.[16] A review of the literature demonstrated that the prevalence of musculoskeletal disorders among keyboard users varied from 9% to 50%, when compared to control groups (low levels of or no keyboard use) where prevalence ranged from 4.5% to 17%.[20,85] The incidence of computer related musculoskeletal disorders remains a serious concern as the number of people using a computer at work continues to steadily rise.

While the literature strongly suggests a causal relationship between computer keyboarding and musculoskeletal disorders of the upper extremity, the association between keyboarding and CTS is not well-established. A systematic review of eight studies of computer work and carpal tunnel syndrome, performed by Thomsen et al., showed that there was insufficient epidemiological evidence that computer work causes carpal tunnel syndrome.[24] In fact, a few studies have concluded that prevalence of carpal tunnel syndrome in computer users is similar to that in the general population. In a study conducted by Stevens et al.,[25] the frequency of carpal tunnel syndrome in computer users at a medical facility was reported to be comparable to that in the general US population. Hou et al. also found a similar prevalence of carpal tunnel syndrome in a group of video display terminal workers to that of the general population.[26] However, the case definition and dose measurement were not clear in these two studies. In addition, there was little difference in hours of keyboarding between the computer users in the former study. In a study of professional technicians, Andersen et al. reported no relationship between keyboard use and incidence of carpal tunnel syndrome. However, most of the participants in the study used a keyboard less than 20 hours per week.[27]

On the other hand, several research studies have demonstrated a correlation between computer keyboarding and carpal tunnel syndrome. A population survey of clinically and electrodiagnostically confirmed carpal tunnel syndrome suggested an association with computer use.[28] Liu et al. reported that the prevalence of carpal tunnel syndrome among computer users at their medical facility was 16.7%,[29] almost 3 times higher than the general population. Moreover, a number of epidemiologic studies have demonstrated the risk of carpal tunnel syndrome is increased with keyboard use above 20 hours per week.[31,32] Using MRI to visualize acute changes in the median nerve as a result of continuous keyboarding, Shafer-Crane reported that the median nerve long axis/short axis ratio decreased in subject without carpal tunnel syndrome symptoms after three hours of keyboarding, while symptomatic subjects demonstrated no significant changes in their median nerves.[34]

The controversial results regarding the association between keyboarding and carpal tunnel syndrome indicate that we have an insufficient understanding of an association between keyboarding and upper limb neuropathy. Assessing acute median nerve changes may be useful in predicting the likelihood of developing carpal tunnel syndrome and evaluating the risks involved with certain tasks. The purpose of this study was to use ultrasonographic measurements to determine whether continuous keyboarding can cause acute changes in the median nerve. Ultrasonography is relatively inexpensive, noninvasive, requires short examination times, and can be used even in non-clinical settings.[35]

Ultrasound has been established as a reliable diagnostic tool for detecting peripheral nerve injuries, including carpal tunnel syndrome.[37,38,40,85,86] It has been used to make accurate measurements of the shape, size, and even movement of the median nerve at various levels of the wrist.[35,37,38,40,85] Several studies have compared ultrasonographic characteristics of the median nerve with electrodiagnostic and clinical examinations in individuals with carpal tunnel syndrome. The most common findings included an increased median nerve cross-sectional area (CSA) at the level of the pisiform bone, increased flattening ratio at the level of the hook of the hamate, and an increased swelling ratio, defined as the ratio of the median nerve CSA at the pisiform level to that at the distal radius level.[35,37,38,40,85] We hypothesized that the median nerve would exhibit a larger cross-sectional area at the pisiform level, an increased swelling ratio, and an increased flattening ratio at the pisiform level following a continuous keyboarding task when compared to baseline images collected prior to keyboarding.

2.2 METHODS

2.2.1 Subjects

A convenience sample of twenty-one healthy volunteers participated in this study. Prior to testing, the participants were screened for any hand symptoms, prior history of median neuropathy, or history of trauma, surgery or underlying conditions related to CTS by filling in a questionnaire. All participants self-reported that they were expert typists (i.e., typing at least 40 words per minute), used a keyboard at least four hours a day, three days a week, and typed using all digits. In order to minimize the effects of prior actions, all subjects were asked to refrain from intense physical activity for 48 hours prior to testing.

2.2.2 Data Collection

2.2.2.1 Quantitative Ultrasound Examination

The details of the quantitative ultrasound examination were described elsewhere.[52,54] Briefly, ultrasound images of the carpal tunnel, with primary emphasis on the median nerve, were collected at the distal radius and the pisiform levels. These two regions are easily viewed using ultrasound and nerve measures. Changes at these locations have previously been linked to carpal tunnel syndrome both electrodiagnostically and symptomatically.[35,37,38,40,85,86] Our laboratory has demonstrated good reliability of intra-rater measures of median nerve ultrasound characteristics, including the cross-sectional area, swelling ratio, and flattening ratio at the pisiform and distal radius levels.[52,54]

Images were obtained using a Philips HD11 XE ultrasound machine with a 5-12 MHz 50 mm linear array transducer (Philips Medical Systems, Bothell, WA, USA). The machine settings were optimized as in our previous studies and held constant across all participants.[52,54] The ultrasonographic images were collected while participants remained seated with upper arm relaxed and fully adducted with no internal/external rotation, the elbow flexed to 90 degrees, forearm supinated and supported, and the wrist maintained at neutral posture with the fingers relaxed. The baseline images were collected prior to participation in the keyboarding task and served as a reference for comparing the post-keyboarding measurements in order to quantify acute changes of the median nerve. Figures 2 and 3 show sample ultrasound images collected, depicting the median nerve and bony landmarks at the carpal tunnel.

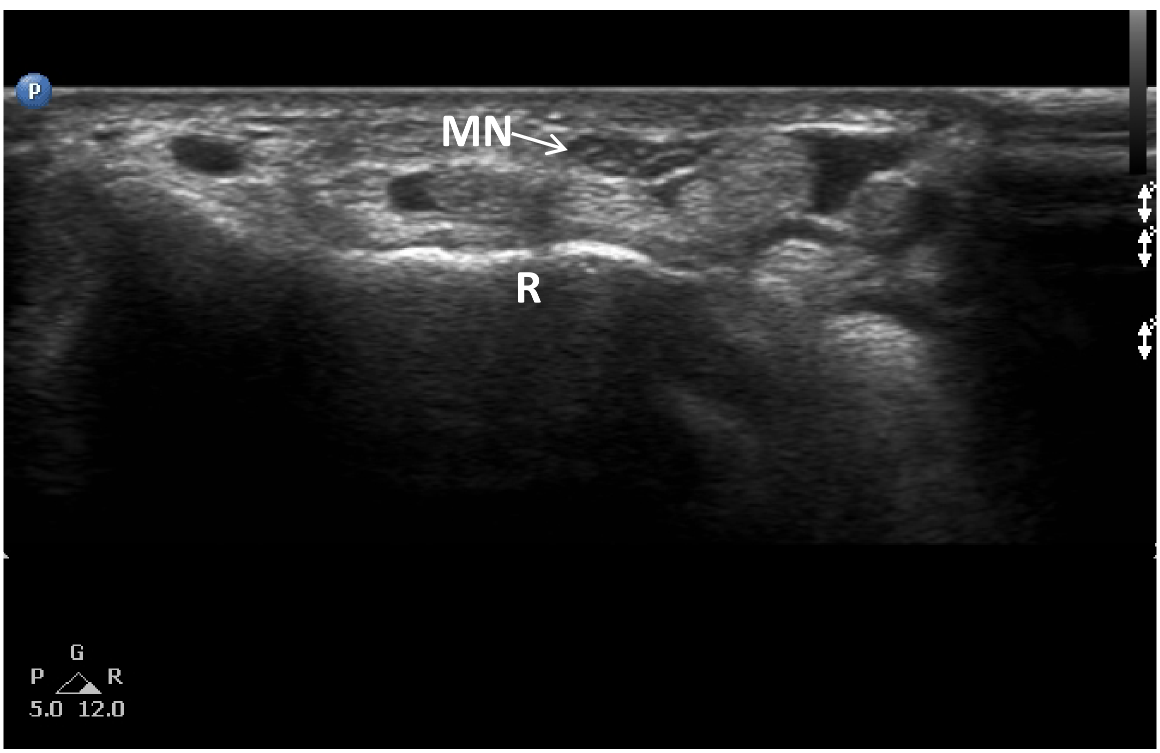


Figure 2. Sample ultrasound image at the distal radius (R) level showing a cross-sectional image of the median nerve (MN)

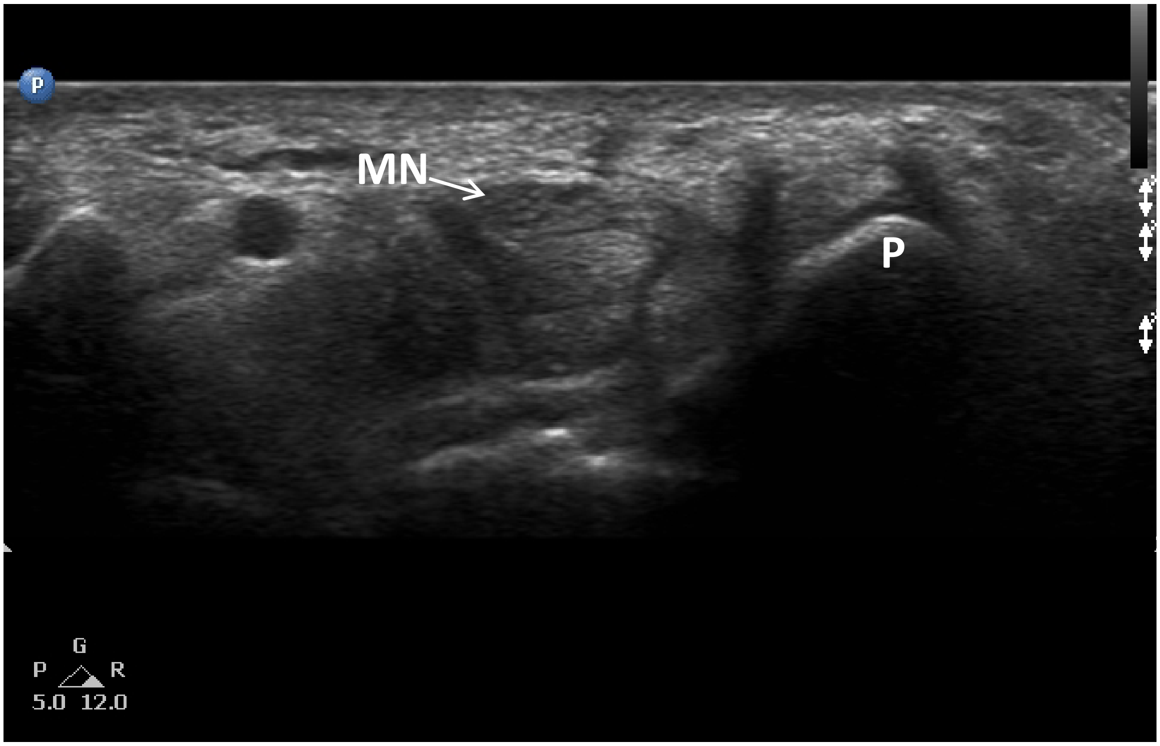


Figure 3. Sample ultrasound image at the pisiform (P) level showing a cross-sectional image of the median nerve (MN)

2.2.2.2 Continuous Keyboarding Task

All keyboarding was completed on an L100 Dell keyboard (Dell, Inc., Round Rock, TX, USA) set in a ‘‘standard’’ (i.e., flat and non-angled) position. For this experiment the height of the chair and workstation were fully adjustable and the subjects were able to set the chair and desk height according to their own preference. The chair did not have armrests. The subjects directly faced a flat screen monitor and were instructed to type at their normal rate on the keyboard, using their usual style. The keyboarding task was performed using an electronic keyboarding program, Typing Master Pro™ (Typing Master Finland, Inc., Helsinki, Finland), which presents a keyboarding test for the keyboard user on the computer screen. The program provides cues as to where they are in the text and advances the text automatically as the keyboard user works through the paragraph. Alternate input devices (i.e., mouse) were not used.

Productivity data, such as keyboarding speed and accuracy, were gathered automatically. After the baseline ultrasound examination, participants typed for 30 minutes and then paused for another ultrasound examination on both wrists. The interruption in keyboarding for this examination lasted less than 10 minutes. Subjects then proceeded to type for another 30 minutes before the final ultrasound examination.

2.2.3 Data Analysis

An interactive semi-automated MATLAB (The MathWorks, Inc., Natick, MA, USA) image analysis program was previously developed to make manual measurements of structures of interest within the ultrasound images.[52,54] Briefly, median nerve diameter and cross-sectional area were determined by performing a boundary trace along the border between the hypoechoic inner median nerve and the hyperechoic outer epineurium. Figure 4 shows examples of the boundary trace and major and minor axis selections. A single investigator, blinded to occasion and image number, analyzed each image to obtain CSA and measures of the major and minor axes of the nerve. We collected these measurements at each image level and calculated the flattening ratio (major axis / minor axis) at pisiform level, and the swelling ratio, defined as CSA at pisiform level divided by CSA at distal radius. Furthermore, in order to minimize the effects of nerve's original CSA, we defined a new variable, ΔCSA, which was calculated as the difference between baseline CSA and CSA after 60-minute keyboarding divided by the baseline value. The ΔCSA was used to compare median nerve changes between dominant and non-dominant hands, and also between male and female participants.

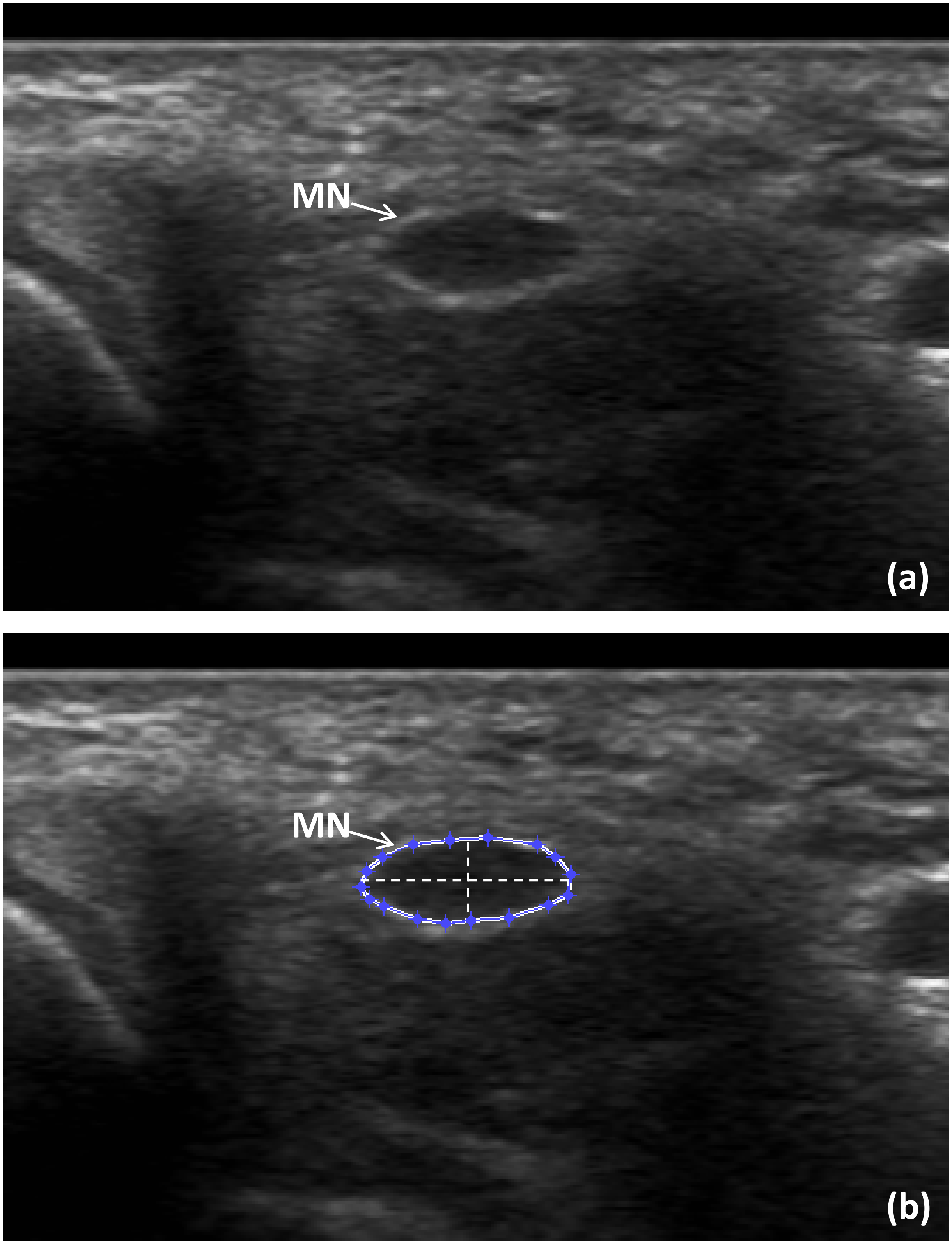


Figure 4. Example of the image analysis selections. The images show a close up of the median nerve (MN) (a) and the same image with the boundary trace (dotted line) and the major and minor axes (dashed lines) selected during the image analysis (b)

2.2.4 Statistical Analysis

Two-way Repeated Measures Analysis of Variance (RM ANOVA) were performed using a commercial statistics software package (SigmaStat; SPSS Inc., Chicago, IL, USA) for each nerve variable comparing the amount of change observed in subjects at each time point (i.e., at the baseline and after 30 minutes and 60 minutes of keyboarding) and for both dominant and non-dominant wrists. If the RM ANOVA was significant, it was followed by the pair-wise multiple comparison procedures (Holm-Sidak method). A p-value of <0.05 was considered statistically significant. Correlation between subject characteristics and median nerve measures at all time points was tested using a regression model, where the dependent variables were the change in the median nerve cross-sectional area, swelling ratio, and flattening ratio. The independent variables of interest included the subject age, gender, and keyboarding speed.

2.3 RESULTS

2.3.1 Subject Characteristics

Of the 21 subjects enrolled in the study, one male participant was excluded (due to median nerve bifurcation). Table 1 summarizes the subject characteristics.

Table 1. The subject characteristics, including gender, age, handedness, keyboarding gross speed, and keyboarding accuracy

	#	Mean Age ± SD (Range)	Right-handed (%)	Mean Gross Speed (wpm) ± SD (Range)	Mean Accuracy ± SD (Range)
Male	9*	29.3 ± 4.5 (23-37)	5 (62.5%)	53.1 ± 10.8 (34-70)	95.3 ± 2.9 (90-98)
Female	12	30.1 ± 7.7 (22-45)	11 (91.7%)	57.7 ± 11.5 (38-75)	93.0 ± 2.4 (90-97)
Total	20*	29.8 ± 6.5 (22-45)	16 (80%)	55.9 ± 11.1 (34-75)	93.9 ± 2.8 (90-98)

* One male subject was excluded due to the median nerve bifurcation.

wpm: words per minute. SD: standard deviation.

2.3.2 Acute Changes in the Median Nerve Measures

2.3.2.1 Baseline Characteristics

The only significant differences between dominant vs. non-dominant side at the baseline was the flattening ratio, which was higher in the dominant wrist (Table 2).

Table 2. The median nerve ultrasound characteristics in dominant (D) and non-dominant (N) hands at baseline and following 30-minute and 60-minute of keyboarding

		Baseline Mean ± SD (Range)	**30-minute Mean ± SD (Range)**	**60-minute Mean ± SD (Range)**
Cross-sectional area (mm^2)	D	10.01 ± 3.41 (5.26-19.12)	10.36 ± 3.82 (5.71-19.59)	10.70 ± 3.86* (4.81-20.03)
	N	9.92 ± 3.78 (5.62-21.27)	10.26 ± 3.85 (5.85-21.13)	10.53 ± 3.71* (5.59-21.36)
Swelling ratio	D	1.11 ± .23 (.91-1.72)	1.17 ± .22 (.68-1.61)	1.25 ± .29* (.98-1.69)
	N	1.14 ± .22 (.83-1.61)	1.18 ± .25 (.84-1.68)	1.19 ± .18 (.93-1.63)
Flattening ratio	D	3.28 ± 1.10 (1.68-6.30)	3.13 ± .94 (2.39-5.68)	3.36 ± .91 (2.50-5.67)
	N	2.89 ± .81** (1.64-4.98)	3.13 ± 1.31 (1.93-6.98)	3.06 ± 1.01 (1.32-5.55)

* indicates significant differences when compared to the baseline values.

** indicates significant differences when compared to the dominant side.

SD: standard deviation.

2.3.2.2 The Cross-Sectional Area

The CSA at the pisiform level showed an increasing trend from the baseline to 30-minute (3.5%) and 60-minute time points (7%) in both dominant and non-dominant wrist. The cross-sectional area of the median nerve at the pisiform level was statistically different following 60 minutes of keyboarding ($p = 0.004$ in dominant side and $p = 0.001$ in non- dominant side), when compared with the baseline values (Table 2).

2.3.2.3 The Swelling Ratio

The swelling ratio also increased gradually following the 30-minute and 60-minute keyboarding task in both the dominant and non-dominant wrist. The increase in the swelling ratio was only significant at the 60-minute time point in the dominant side ($p=0.020$), when compared to the swelling ratio at the baseline (Table 2).

2.3.2.4 The Flattening Ratio

The flattening ratio was the only variable which was significantly higher (13.6%, $p=0.047$) in the dominant median nerve than the non-dominant nerve at the baseline. The RM ANOVA was not significant for either wrist after 30-minutes and 60-minutes of keyboarding in either wrist, when compared to each other or to the flattening ratio values at the baseline (Table 2).

2.3.3 Relation between the Median Nerve Measures and Subject Characteristics

There was a significant positive correlation ($p<0.001$) between subject age and the CSA in both hands, at baseline ($r=0.702$) and also after 60-minutes of keyboarding ($r=0.739$). In addition, changes in the nerve cross-sectional area (i.e., ΔCSA) in the dominant hand were significantly different ($p=0.033$) in male subjects (11.3 ± 3.3 mm^2) from those of female participants (2.9 ± 2.0 mm^2). Keyboarding speed demonstrated no significant correlation with any of the median nerve variables or changes detected in the nerve measures at different time points.

2.4 DISCUSSION

This study found that specific median nerve ultrasound measures, which had been previously linked to carpal tunnel syndrome, changed significantly after 60 minutes of keyboarding. In particular, CSA and swelling ratio demonstrated significant increases from the baseline to the 60-minute time point. Although the cross-sectional area at the pisiform level and swelling ratio showed 5% and 3.5% increases, respectively, compared to the baseline values after 30 minutes of keyboarding, both CSA and swelling ratio became significantly different from the baseline only after 60 minutes of keyboarding in the dominant wrist. These findings are consistent with those of previous studies[34,86] and support the idea that changes in the median nerve are dose related.

In contrast to the cross-sectional area and swelling ratio, the baseline values of the flattening ratio were significantly different between dominant and non-dominant wrists at baseline, but not after 60 minutes. In fact, flattening ratio was significantly higher in the dominant median nerve than the non-dominant nerve at the baseline. It appears that the median nerve in the dominant hand might demonstrate changes due to other activities of daily living prior to testing, which would cause a significantly higher flattening ratio in the dominant side than in the non-dominant one at the baseline. However, following the 60-minute keyboarding task, the non-dominant hand showed greater changes in the flattening ratio, which resulted in its "catching up" with the dominant side. This might indicate that keyboarding is not necessarily a symmetrical task as suggested by other studies.[88] Further studies are required to address why the flattening ratio is the only median nerve measure to demonstrate such behavior.

In general, epidemiological studies have shown carpal tunnel syndrome to be more prevalent in females and in elders.[2,89] The results of this study with regard to age support these studies, as there was a significant positive correlation between the median nerve CSA and subject age. Our results did not show any significant differences in the median nerve characteristics between male and female participants. However, the ΔCSA was significantly higher in male subjects. Further study is needed to evaluate the effect of gender on the median nerve characteristics following a keyboarding task.

Ultrasound has been previously used as a research tool for quantifying the acute response of the median nerve to repetitive activity.[48,49,52] The magnitude of change in median nerve measures in the previous studies, including one in our laboratory, ranged from 4 to 20%, while a majority were rather small changes of less than 10%. In this study, using ultrasound, we were able to detect changes in the median nerve CSA, swelling ratio, and flattening ratio which varied from 3.5% to 12.7%. These results were consistent with the previous research work. While acute changes in the median nerve measures following a prolonged keyboarding task were significant and relatively dose-dependent, longitudinal studies are needed to determine long-term changes.

2.4.1 Limitations

Research has shown that there is great variety in preferred postures/styles among different keyboard users that appear to be related to the physical characteristics of the workstation.[55,59,63,90] In this study, we did not attempt to recreate each subject's work set up as we believe attempting to recreate the workstation would add variability to the experiment. Future studies, however, need to investigate the potential effects of physical set up of the workstation on the median nerve measures. Although we took many steps to limit participants' physical activity prior to testing, we were unable to fully control the relative rest of the subjects participating in this study. Minimizing participants' activities prior to testing should be a major consideration for the future studies. Furthermore, small sample size (N=20) and unequal number of participants from each gender (8 males vs. 12 females) made it difficult to draw a conclusion regarding the effect of gender on the median nerve characteristics following a keyboarding task.

Larger sample size and recruiting equal numbers of male and female subjects will help future studies elucidate the role of gender on the acute changes of median nerve. Means and standard deviations from these data could be used to estimate the statistical power in future studies. For example, the primary effects of interest are the differences between the pre- and post-keyboarding measurements of the median nerve. Using these data, the required sample size for a range of statistical power (80%, 85%, 90%) with two sided α=0.05 on the paired t-test would be 27, 31, and 35, respectively.

Finally, this study did not investigate any further changes in the median nerve characteristics that could have occurred after a period of rest following the keyboarding task. One can speculate that the acute changes in the median nerve that were caused by prolonged keyboarding would diminish upon resting the upper extremities. Therefore, a reasonable resting period followed by an additional round of ultrasound examination should be considered in future studies.

2.5 CONCLUSIONS

The median nerve exhibited acute changes in response to a keyboarding task. This is further evidence of a potential causal relationship between computer keyboarding and median nerve injuries such as carpal tunnel syndrome. Further studies, however, are required to elaborate on any possible pathophysiologic mechanism. Specifically, longitudinal studies could be designed to follow up median nerve changes in participants who continue keyboarding in a frequent manner. In addition, investigating biomechanical measures related to keyboarding, such as forearm and/or wrist posture and angles, finger positioning and movements, and forces and motions experienced by the wrist, would provide insight into the pathophysiology of median nerve injury. This may provide an opportunity to develop interventions specific to these biomechanical risk factors. Inclusion of subjects with known median nerve pathology (e.g., diagnosed carpal tunnel syndrome patients) in such a study may help investigators differentiate the median nerve response to a repetitive task, like keyboarding, in a physiologic as opposed to a pathologic condition, since it has been shown that changes in the median nerve resulting from keyboarding may be less likely to occur in subjects with symptoms of carpal tunnel syndrome.[34]

3.0 CHAPTER II

KEYBOARDING BIOMECHANICS AND ACUTE CHANGES OF THE MEDIAN NERVE

3.1 BACKGROUND

It was previously demonstrated that a continuous keyboarding task can cause acute changes in the ultrasonographic measures of the median nerve. Particularly, 60 minutes of computer keyboarding resulted in significant increase in the cross-sectional area and swelling ratio of the median nerve. While the results of our pilot study were consistent with those of other research studies,[91] the mechanisms responsible for these changes were not understood. Carpal tunnel pathophysiology and keyboarding mechanics data demonstrate that it is likely that the changes in the median nerve are physiological responses to repetitive use and not specific to keyboarding. Since the median nerve moves and deforms inside the carpal tunnel with changes in the position of nearby joints, muscles, and tendons, it may be possible to relate specific biomechanics to nerve histology. In order to assess tissue response to continuous keyboarding a detailed and comprehensive model of keyboarding mechanics is necessary. While finger joint kinematics during keyboarding have been extensively analyzed, currently available keyboarding mechanics data have failed to show how keyboarding can contribute to median nerve injury.

3.1.1 Significance

Carpal tunnel syndrome (CTS) is one of the most common musculoskeletal disorders of the upper extremities and has become one of the fastest growing occupational disorders in the United States, increasing over 60% in data entry/typing jobs over the past decade.[2] Its prevalence among individuals in keyboarding-intensive jobs suggests that keyboarding may be contributing to median nerve injury. While epidemiological evidence suggests keyboarding plays a role in CTS development, this association is not well-established. Although multiple studies examined kinematics of the wrist and fingers during keyboarding in depth,[59,92] to best of our knowledge, no one has investigated the relationship between keyboarding kinematics and acute changes of the median nerve as a result of keyboarding. This study aims to establish a baseline understanding of keyboarding biomechanics in healthy subjects as they relate to acute changes in the median nerve during prolonged keyboarding.

3.1.2 Pathophysiology of Carpal Tunnel Syndrome

The most prevalent and accepted theory for the pathogenesis of CTS is compression of median nerve in the carpal tunnel.[4,5] Although this theory is widely accepted, the cause of the compression in the carpal tunnel is not fully understood. In the following sections we will discuss the literature that proves the association between CTS and median nerve compression. In addition we will review the literature related to the cause of the compression.

3.1.2.1 Task Frequency

In a study of 700 manufacturing and clerical workers, Werner et al. found that the 184 active workers with electrodiagnostic evidence of median mononeuropathy performed jobs with a higher level of hand repetition.[93] Silverstein et al. performed a biomechanical investigation of a number of jobs and stratified these to determine the risk of CTS.[6] Silverstein found that high force and high repetition jobs were associated with CTS. Loslever in a study of risk factors for CTS in the workplace, found frequency of performing a task to be associated with CTS.[2] In looking at motion repetitiveness, Roquelaure et al. studied 130 workers, half of whom had CTS. This research found factors related to frequency of a task to be more highly correlated with CTS than wrist posture or forces.[9] The studies by both Silverstein and Roquelaure indicated that high frequency was a greater risk factor for CTS than high force.

Previous work on wheelchair propulsion confirms the importance of repetition in the development of median nerve injury.[94] In this study individuals with evidence of median nerve injury on nerve conduction studies pushed with greater frequency than individuals without evidence of injury to go the same speed (Figure 5).

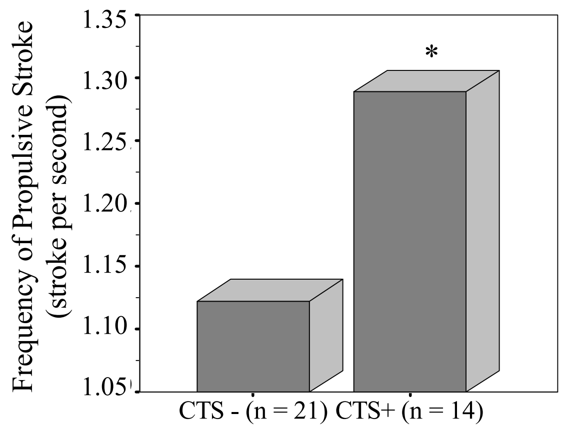


Figure 5. Individuals with evidence of CTS had a greater frequency of propulsion strokes than individuals without CTS to go the same speed.[94] Asterisk indicates significant difference.

3.1.2.2 Canal Diameter

Both plain radiographs and MRI studies have been used to investigate the relationship between shape and size of the carpal tunnel and risk of CTS. The basis for these studies is that certain individuals are at greater risk for median nerve compression and thus CTS due to small diameter carpal tunnels. Pierre-Jerome et al. used MRI to determine carpal canal volumes in two separate studies.[95,96] In a group of floor cleaners at high risk for CTS, he found no association between canal volume and electrophysiologic testing of the median nerve.[96] In a separate study, he found women with idiopathic CTS had the same size carpal tunnel as a group of healthy controls.[95] From these studies they concluded that the size of the carpal canal did not play a role in the pathogenesis of CTS. Cobb et al. performed a cadaveric study to determine the ability of MRI to measure the contents of the carpal tunnel.[97] This study found a high correlation between MRI determined volume and actual measurements. Thus they were able to adequately measure tendon and nerve volumes using a known correction factor.

3.1.2.3 Loading of the Wrist

In addition to investigating the effect of position on hydrostatic carpal tunnel pressure, Keir et al. investigated the effect of loading of the flexor tendons. This study used a catheter and a bulb transducer in eight cadaver hands.[98] Each hand was moved through various angles of flexion and extension as well as different angles of radial and ulnar deviation. Pressure at the different positions was measured while loading the palmaris longus and flexor pollicis longus with weights. This study found that hydrostatic carpal tunnel pressure was greatest in extension and in ulnar deviation with the palmaris longus loaded. The loaded condition was meant to simulate muscle activity.

Werner et al. used videotapes of working tasks to classify jobs. Jobs rated as being higher force were related to the risk of CTS.[93] Roquelaure et al. used the weight of tools and parts handled to determine forces exerted at the hand.[9] This study found that lifting an object weighing greater than 1 kg in mass was associated with CTS (odds ratio = 9.0). Armstrong's study of work related risk factors for CTS found individuals with CTS used higher forces in all positions than individuals without CTS who were performing the same work task.[99] Silverstein et al. performed biomechanical investigation of a number of jobs and stratified these to determine the risk of CTS.[6] Although repetition appeared to be a more important factor, high force activities were also associated with risk of CTS. High force was defined as average hand force of more than 39 N while low force was defined as below 9.8 N. Loslever et al. studied factors associated with the early development of CTS in high-risk jobs.[2] The time spent exerting forces over 20 N was found to correlate with the early development of CTS.

3.1.3 Keyboarding Kinematics

Several studies investigated the keyboarding kinematics and correlation between keyboarding and the development of musculoskeletal disorders of the upper extremities (MSD-UE). The majority of studies have found that prolonged computer use is associated with MSD-UE. The prevalence of keyboard related MSD-UE has been estimated to be between 9% and 50% of computer users and the odds ratios of computer-related MSD-UE range from .5 to 10.1.[20] The incidence of MSD-UE related to computer users has been identified in several studies. Hales et al.[32] found that 22% of 108 telecommunication computer users reported MSD-UE: 12% wrist/hand problems; 9% neck problems; 7% elbow problems; and 6% shoulder problems.

Bergqvist et al.[18] indicated that 23% of 252 VDT workers had a diagnosis of MSD-UE of the neck; 12% had a diagnosis of a shoulder disorder; and 9% had a diagnosis of a wrist or hand disorder. Gerr et al.[84] reported that 20% of their sample incurred a neck/shoulder disorder after 12 months of computer use and 13% had hand/arm symptoms. Overall, it would appear that approximately 22% of computer users sustain MSD-UE.

3.1.3.1 Wrist Posture during Keyboarding

Despite great variety in preferred postures among different keyboard users,[56,57,100] research suggests that individual keyboarding kinematics are relatively stable and unchanging during keyboarding tasks.[58,59] The postures assumed do not appear to be necessarily related to the anthropometrics of the keyboard user,[57] but do appear to be related to the physical characteristics of the workstation,[60-67] suggesting that a well-controlled workstation is necessary to minimize introducing unwanted variables.

Studies suggest that standard keyboard users maintain their left wrist an average of 66 degrees (± 8.3) pronation, 15 degrees (± 7.7) ulnar deviation, and 21 degrees (± 8.8) extension; and the right wrist at 62 degrees (± 10.6) pronation, 10 degrees (± 7.2) ulnar deviation, and 17 degrees (± 7.4) extension.[57] These postures vary considerably from subject to subject. Although pronation has been hypothesized to be a risk factor,[68] little research has been completed to determine the effect of pronation on repetitive strain injury. Ulnar wrist deviations of 20 degrees or more have been associated with repetitive strain injury and increased pain/discomfort.[69] Epidemiological studies that have examined the relationship between wrist extension and musculoskeletal pain/discomfort have generally not found a significant association between the two.[69-71] This has not prevented researchers from hypothesizing the safe level of wrist posture. Assessment tools have set 15 degrees or less of wrist extension as a safe posture.[72,73]

A number of investigators have examined the association between CTS and wrist posture by measuring the pressure in the carpal canal in various positions. Tanzer appeared to be the first to investigate carpal tunnel pressure changes with respect to wrist position.[101] During CTS surgery he found that pressure increased in the proximal portion of the tunnel during flexion and extension, while only extension increased pressure in the distal portion. Since this initial study, a number of investigators have confirmed that extremes of wrist flexion and extension can greatly increase the pressure within the carpal tunnel, more so in patients with CTS.[102,103] In one study, 18 individuals with paraplegia (IWP) had manometric studies performed with their wrist in various positions. IWP had higher pressures in wrist extension than control subjects without paralysis but with CTS.[104]

Another group of investigators have examined wrist posture in a work setting as a risk factor for CTS. Armstrong et al. examined posture and force in a group of 36 women, half of whom had CTS.[99] Using cinematography to measure position, this study found women with CTS were in a position of wrist extension more frequently than those without CTS. Werner et al. used video tapes to rate posture and force exerted during repetitive tasks.[93] He found abnormal posture to be associated with symptoms and nerve conduction evidence of CTS.

3.1.4 Rationale

Carpal tunnel syndrome is a common, costly problem in the general population and more so in manual workers.[1,3] The most accepted theory for the pathophysiology of CTS is compression of the median nerve in the carpal tunnel.[4,5] While the cause of this compression is unknown, research suggests high-repetition, high-force tasks contribute to median nerve injury.[6,9] Ultrasound can measure the shape and size of the median nerve at various levels of the wrist and has been used for diagnosing CTS.[35,37,38,40,52,54,85,86] We have used ultrasonography to investigate changes in the median nerve with repetitive activity and believe that the changes detected may be useful in predicting the likelihood of developing CTS and assessing the risks involved with a task.[91] The purpose of this study was to use ultrasound techniques to identify acute changes in the median nerve occurring as a result of keyboarding, and to correlate these changes with wrist biomechanical variables during keyboarding. Using ultrasound, acute changes in the median nerve were quantified. During the keyboarding task kinematic and kinetic data were also collected and a biomechanical model of hand was developed. Finally, using statistical analyses, the correlation between acute changes in the median nerve ultrasound measures and biomechanical variables of the hand and wrist during keyboarding was investigated.

3.2 HYPOTHESES AND SPECIFIC AIMS

3.2.1 Specific Aim 1

The first Specific Aim was to identify acute changes in the median nerve at the wrist after a period of keyboarding using ultrasound techniques. It was hypothesized that following a continuous keyboarding task the median nerve will exhibit the following changes when compared to baseline images collected prior to keyboarding:

1) A larger cross-sectional area (CSA) at the pisiform level;
2) Increased swelling ratio (CSA at pisiform level / CSA at distal radius);
3) Increased flattening ratio (nerve width divided by nerve height) at the pisiform level.

3.2.2 Specific Aim 2

Specific Aim 2 was to measure wrist and hand biomechanical variables and determine their association with acute changes observed in the median nerve due to keyboarding. The hypothesis was that acute changes in the median nerve, described in Specific Aim 1, would be positively correlated with the following biomechanical variables collected during keyboarding:

1) Average peak ulnar deviation of the wrist and average peak wrist extension;
2) Average keystroke forces;
3) Typing speed (words per minute);
4) Average peak resultant flexor tendon travel.

3.3 METHODS

3.3.1 Subjects

Forty participants were recruited from employees working at the Department of Veterans Affairs and the University of Pittsburgh. In order to be included participants had to (1) be between 18 and 65; (2) speak English; (3) self-report to be a proficient typist; (4) use a keyboard at least three hours a day, four days a week; and (5) type using at least 8 digits. Exclusion criteria include: (1) history of wrist surgery or fracture; (2) self-report or present clinical or electrophysiological evidence of an accompanying condition that mimics CTS or interferes with its evaluation, such as proximal median neuropathy, cervical radiculopathy or polyneuropathy; and (3) history of underlying disorders associated with CTS such as diabetes mellitus, rheumatoid arthritis, pregnancy, acromegaly or hypothyroidism. As such, all the participants were free of hand symptoms and had no clinical or electrodiagnostic median abnormalities.

3.3.2 Study Procedures

Subjects were considered enrolled in the research study once they signed informed consent but prior to the initiation of study procedures. Participants were asked to refrain from intense physical activity such as sports, exercise, repetitive forceful arm tasks like yard work for 48 hours, and vigorous typing, for 12 hours prior to participation in this study since intense physical activity may affect the baseline measurements. Participants were scheduled in the morning in order to limit the amount of activities performed on the day of testing. Limiting the subject's activity level prior to testing helped ensured that the baseline ultrasonography captured the typical state of the median nerve.

Once enrolled in the study, each participant completed the following tests and measurements:

1) General Intake Information and Hand and Wrist Pain questionnaires
2) Anthropometric measurements
3) Baseline quantitative ultrasonography exam
4) Biomechanics data collection during first continuous 30-minute keyboarding task
5) Quantitative ultrasound exam at the end of the first continuous 30-minute keyboarding task
6) Biomechanics data collection during second continuous 30-minute keyboarding task
7) Post-keyboarding quantitative ultrasound exam immediately after second keyboarding task
8) Quantitative ultrasonography exam 30 minutes after second keyboarding task

3.3.3 Data Collection

3.3.3.1 General Intake Information

Prior to the baseline ultrasound exam, participants were asked to complete General Intake Information and Hand and Wrist Pain Questionnaire. The primary measures derived from these questionnaires were basic demographics, including age, gender, height and weight, ethnic background and hand-dominancy, work history, and history of medical problems. The questionnaires require about one hour for completion which provided a rest period for participants thus standardizing the amount of activity each subject performs immediately prior to the baseline ultrasonography exam. Anthropometric measurements of the upper extremity, including wrist circumference and length of finger segments, were also recorded.

3.3.3.2 Quantitative Ultrasonography Examination

Ultrasonographic images were collected using a Philips HD11 XE ultrasound machine with a 5-12 MHz 50 mm linear array transducer (Philips Medical Systems, Bothell, WA, USA). Images of the carpal tunnel, with primary emphasis on the median nerve, were collected at the distal radius and the pisiform levels. These regions are easily viewed using ultrasonography and nerve characteristics at these locations have previously been linked to CTS both electrodiagnostically and symptomatically.[35,38] Baseline images were collected prior to participation in the keyboarding task. The baseline examination served as a reference for comparing the post-keyboarding measurements in order to quantify acute changes of the median nerve. We also performed an ultrasonography examination between two 30-minute typing trials and completed ultrasonography examinations at two time points post-keyboarding; one immediately after the keyboarding task was complete, and one final ultrasonography examination 30 minutes later, while subjects rested their hands.

3.3.3.3 Continuous Keyboarding Task

All keyboarding were completed on an L100 Dell keyboard (Dell, Inc., Round Rock, TX, USA) set in a “standard” (i.e., flat and un-angled) position. The participants directly faced a flat screen monitor and were able to set the desk and chair height according to their own preference. We did not attempt to recreate the participant’s work set up as we believe attempting to recreate the workstation will add variability to the experiment. Participants were asked to remove their wrist watch and/or wrist brace and instructed to type at their normal rate on the keyboard, using their usual method. Alternate input devices (i.e., mouse) were not used. All participants typed the same text. Participants were instructed not to correct errors generated while typing.

The keyboarding task was performed using an electronic keyboarding program, Typing Master Pro™ (Typing Master Finland, Inc., Helsinki, Finland), which presents a typing task for the keyboard user on the computer screen. The program provides cues as to where they are in the text and advances the text automatically as the keyboard user works through the paragraph. Productivity data, such as typing speed and accuracy were gathered automatically.

3.3.3.4 Wrist Kinematics

Kinematics data were collected using an Optotrak™ motion capture system (Northern Digital, Inc., Waterloo, Ontario, Canada), shown in Figure 6. The hand, wrist, and finger movements were derived from the tracking of active markers positioned on the dorsal surface of the dominant hand and forearm (Figure 7).

Figure 6. Optotrak motion capture system configuration and its set-up with respect to the keyboarding workstation

The markers were attached to the upper extremity using double sided tape. We collected data at 5 and 25 minutes of the testing period for 60 seconds each, as individual keyboarding kinematics are relatively stable during keyboarding tasks.[58,59]

Figure 7. Active markers affixed to the dorsal aspect of the dominant hand during the keyboarding task

3.3.3.5 Force Measurements

Commonly used keys were instrumented and forces applied to keys at each keystroke were collected via FlexiForce®. The force sensors (Figure 8) connect to the ELF™ (Economical Load & Force) system provided by Tekscan, which allowed collecting real-time data using multiple channels (Figure 9). The system was calibrated before each testing session through repeatedly loading the sensors with a known and stable force and obtaining the best linear fit for that load.

Figure 8. Exemplar force sensors provided by FlexiForce that were installed underneath the keyboard keys

Figure 9. The ELF (Economical Load & Force) system provided by Tekscan, which was used to collect real-time data using multiple channels

3.3.4 Data Analysis

3.3.4.1 Ultrasonographic Image Analysis

Details of ultrasound image analysis and related calculations have been described elsewhere.[91] Briefly, an interactive MATLAB image analysis program (The MathWorks, Inc., Natick, MA, USA) was developed to make manual diameter and CSA measurements of structures of interest using the ultrasonography images. The median nerve diameter and CSA were determined via performing a boundary trace by a blinded investigator. Other indicators such as flattening ratio and swelling ratio were calculated post-analysis. The key variables were the ultrasonography measures at the end of the typing task.

Additionally, in order to investigate the actual changes in the median nerve measures, we defined a series of new variables for each median nerve characteristic and designated them with a "Δ" character. Basically, these variables were calculated as the difference between baseline value and the values at 30- and 60-minute time points divided by the baseline value and presented as percentage. For instance, the ΔCSA_30 indicates the difference between the CSA at baseline and 30-minute time point, divided by the baseline CSA times 100.

3.3.4.2 Typing Speed

The typing program automatically measured gross typing speed, adjusted typing speed, and accuracy during both 30-minute keyboarding tasks. The average gross typing speed (in words per minute) and accuracy were calculated for each subject.

3.3.4.3 Kinematics Data

Hand and wrist kinematics, including angles and range of motion, were calculated using local coordinate systems created with the active markers placed on the subject's dominant hand, wrist and forearm (Figure 10).[105,106] We determined the peak flexion/extension angles, peak ulnar/radial deviations, average flexion/extension angles, average ulnar/radial deviations, and range of motion for the wrist and three middle fingers over the course of the kinematic data collection.

Joint angles were derived as described in Baker et al.[59] Briefly, we considered that the metacarpophalangeal (MCP) or proximal interphalangeal (PIP) joint was neutral (or 0°) when the metacarpal bones and/or phalanges formed a straight line. The hand and forearm was modeled as rigid segments and their orientations were derived by tracking their local coordinate systems constructed on the three hand and three forearm markers (the yellow triangles in Figure 10). MCP and PIP joints were assumed to be 2-degree-of-freedom joints, and MCP and PIP flexion/extension and adduction/abduction angles were computed using the 3D angles between the corresponding metacarpals and proximal phalanges, or proximal and intermediate phalange vectors (the red lines in Figure 10).

Figure 10. The location of the markers on the dorsal aspect of the hand and forearm (blue circles) and the hand and forearm planes (yellow triangles) that were defined by their local coordinate systems

3.3.4.4 Statistical Considerations

All statistical analyses were preceded by detailed descriptive analysis of the data, using standard descriptive summaries (e.g., means, standard deviation, percentiles, ranges) and graphical techniques (e.g., histograms, scatter plots). In addition, two-way Repeated Measures Analysis of Variance (RM ANOVA) were performed using a commercial statistics software package (SigmaStat; SPSS Inc., Chicago, IL, USA) for each nerve variable comparing the amount of change observed in subjects at each time point (i.e., at baseline, after first 30 minutes of keyboarding, after 60 minutes of keyboarding, and after 30 minutes of rest following the keyboarding task) and for both dominant and non-dominant wrists. Pair-wise multiple comparison procedures were performed if the RM ANOVA was significant. A p-value of <0.05 was considered statistically significant. Correlations between median nerve measures and wrist biomechanical parameters at each time point were also tested.

3.3.4.5 Linear Regression Analyses

Linear regression models were used to test whether the acute changes in the median nerve were correlated to the wrist biomechanics and/or subject characteristics. The dependent variables of interest were the median nerve cross-sectional area at the pisiform level, swelling ratio, and flattening ratio at 30-minute and 60-minute time points. The independent variables of interest were the baseline values of median nerve measures, subject characteristics, including age, gender (categorical), BMI, keyboarding speed and wrist circumference, as well as biomechanical variables such as wrist position (i.e., peak ulnar deviation and peak wrist flexion) and keystroke reaction forces. Multiple linear regression models were built to predict the value of the three median nerve measures at 30- and 60-minute time points as a function of their baseline values and the individual and biomechanical variables listed above.

3.4 RESULTS

3.4.1 Subject Characteristics

Of the 40 subjects enrolled in the study, two female participants were found to have history of wrist fracture or symptom and signs of carpal tunnel syndrome and were excluded. In addition, one male participant was excluded due to median nerve bifurcation. Table 3 and Table 4 summarize subject characteristics.

Table 3. Subject characteristics, including gender, age, handedness, and keyboarding gross speed and accuracy.

	#	Mean Age ± SD (Range)	Right-handed (%)	Mean Gross Speed (wpm) ± SD (Range)	Mean Accuracy ± SD (Range)
Male	18	27.6 ± 4.9 (20-40)	12 (66.7%)	50.8 ± 10.0 (38-75)	89.3 ± 6.5 (68-97)
Female	19	30.4 ± 7.7 (19-46)	18 (94.7%)	58.6 ± 10.3* (39-78)	89.1 ± 5.3 (80-98)
Total	37	29.1 ± 6.6 (19-46)	30 (81.1%)	54.8 ± 10.8 (38-78)	89.2 ± 5.8 (68-98)

* indicates significant difference when compared to male subjects. wpm: words per minute. SD: standard deviation.

Table 4. The subjects' Body Mass Index and wrist circumference

	Mean Body Mass Index ± SD (Range)	Wrist Circumference (mm)
Male	26.3 ± 3.5 (18.1-32.5)	172.3 ± 10.8 (158-192)
Female	24.1 ± 5.3 (18.4-41.6)	154.9 ± 11.5 (136-181)*
Total	25.2 ± 4.6 (18.1-41.6)	163.4 ± 14.1 (136-192)

* indicates significant difference when compared to male subjects. SD: standard deviation.

3.4.2 Acute Changes in the Median Nerve Ultrasound Measures

3.4.2.1 Baseline Characteristics

No significant differences between dominant and non-dominant sides at the baseline were found (Table 5).

Table 5. The median nerve ultrasound characteristics in dominant (D) and non-dominant (N) hands at baseline, following 30-minute and 60-minute of keyboarding, and also after a 30-minute period of rest after keyboarding (i.e., 90-min)

		Baseline Mean ± SD (Range)	30-minute Mean ± SD (Range)	60-minute Mean ± SD (Range)	90-minute Mean ± SD (Range)
Cross-sectional area (mm^2)	D	10.31 ± 1.82 (7.14-14.94)	10.79 ± 2.11* (6.69-14.66)	10.84 ± 1.81* (7.85-14.92)	10.59 ± 1.77 (6.36-13.33)
	N	10.22 ± 2.46 (6.57-14.46)	10.62 ± 2.56* (7.17-15.34)	10.69 ± 2.54* (7.31-15.22)	10.29 ± 2.42 (7.50-14.19)
Swelling ratio	D	1.01 ± 0.14 (0.81-1.39)	1.08 ± 0.17* (0.81-1.55)	1.09 ± 0.15* (0.86-1.64)	1.05 ± 0.16 (0.75-1.52)
	N	1.05 ± 0.14 (0.87-1.41)	1.12 ± 0.14* (0.86-1.48)	1.11 ± 0.13* (0.87-1.47)	1.06 ± 0.13 (0.85-1.37)
Flattening ratio	D	2.94 ± 0.76 (1.82-5.86)	2.94 ± 0.65 (1.71-5.00)	2.94 ± 0.67 (1.78-4.71)	2.96 ± 0.74 (1.69-5.30)
	N	2.77 ± 0.62 (1.63-4.28)	2.84 ± 0.53 (2.03-4.28)	2.80 ± 0.55 (2.03-4.41)	2.88 ± 0.74 (1.83-4.99)

* indicates significant differences when compared to the baseline values. SD: standard deviation.

3.4.2.2 The Cross-Sectional Area

The cross-sectional area of the median nerve at the pisiform level increased by approximately 5% after 30 minutes and 60 minutes of keyboarding in both dominant and non-dominant wrists (Figure 11). The CSA at the pisiform level was significantly different following 30 minutes of keyboarding ($p = 0.005$ in dominant side and $p = 0.028$ in non- dominant side), when compared with the baseline values (Table 5). The CSA at the pisiform level was also significantly higher at the 60-minute time point in both dominant and non-dominant wrists ($p = 0.004$ and $p = 0.011$, respectively). The results demonstrate that the cross-sectional area of the median nerve decreased after a resting period of 30 minutes and its values at either wrist were not statistically different when compared to the baseline. In fact, the CSA at the pisiform level following half an hour of rest was significantly different at the non-dominant wrist compared to those at the 30-minute and 60-minute time points ($p = 0.048$ and $p = 0.040$, respectively). The CSA at the 30-minute time point was not statistically different from the CSA at the 60-minute time point in either hand.

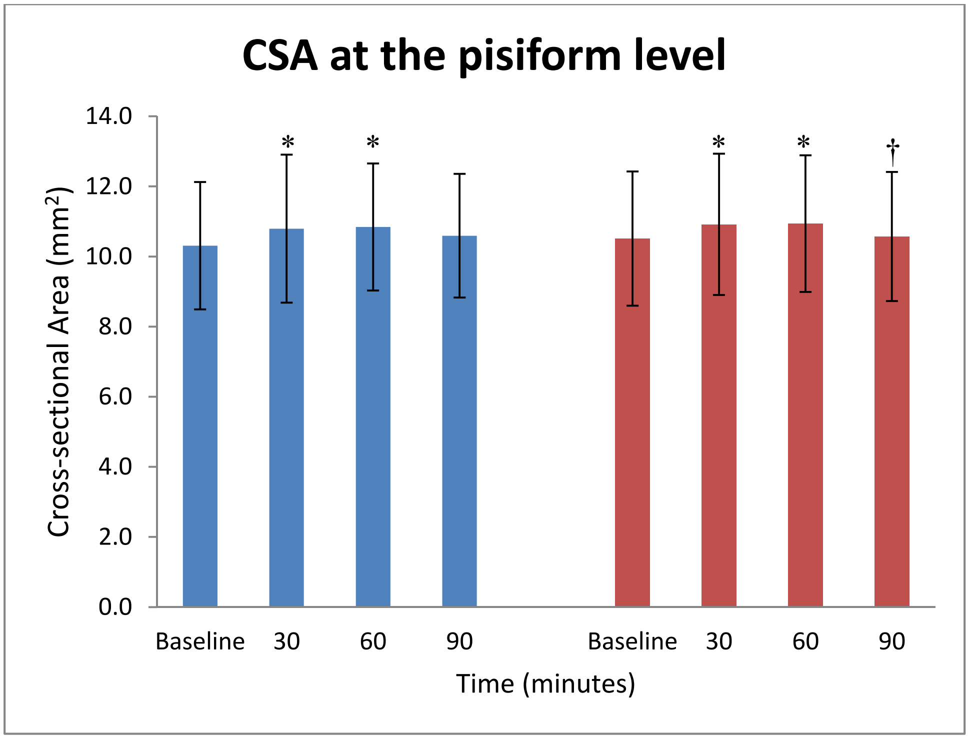


Figure 11. The CSA at the pisiform level in dominant (blue) and non-dominant (red) hands, at the baseline, 30-minute, 60-minute, and 90-minute time points. The asterisks designate significant differences when compared to the baseline values. † indicates significant differences when compared to the 30- and 60-minute data. Error bars represent standard deviations.

3.4.2.3 The Swelling Ratio

The swelling ratio also increased as a result of 30 minutes and 60 minutes of keyboarding in both dominant and non-dominant wrists approximately 6% to 8% (Figure 12). The increase in the swelling ratio was significant at both 30-minute and 60-minute time points in the dominant side ($p = 0.004$ and $p = 0.001$, respectively), and also in the non-dominant side ($p = 0.010$ and $p = 0.008$, respectively), when compared to the swelling ratio at the baseline (Table 5). The swelling ratio decreased following the resting period and was not significantly different from the baseline values in either wrist but had significant differences with those at the 30-minute and 60-minute time points in the non-dominant hand ($p = 0.014$ and $p = 0.041$, respectively). The swelling ratio at the 30-minute time point was not statistically different from the one at the 60-minute time point in either hand.

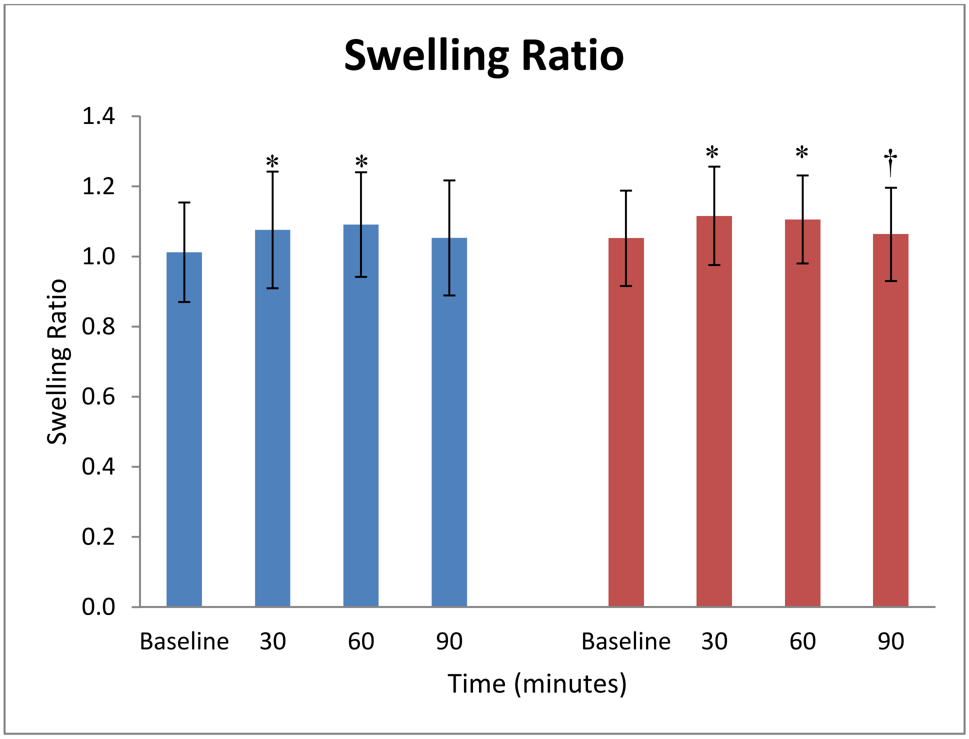


Figure 12. The swelling ratio at the pisiform level in dominant (blue) and non-dominant (red) hands, at the baseline, 30-minute, 60-minute, and 90-minute time points. The asterisks designate significant differences when compared to the baseline values. † indicates significant differences when compared to the 30- and 60-minute data. Error bars represent standard deviations.

3.4.2.4 The Flattening Ratio

The flattening ratio demonstrated no significant changes as a result of 30 minutes and 60 minutes of keyboarding in either wrist, when compared to each other or to the flattening ratio values at the baseline (Figure 13 and Table 5). The values for the flattening ratio after the resting period were not significantly different compared to those at the other time points.

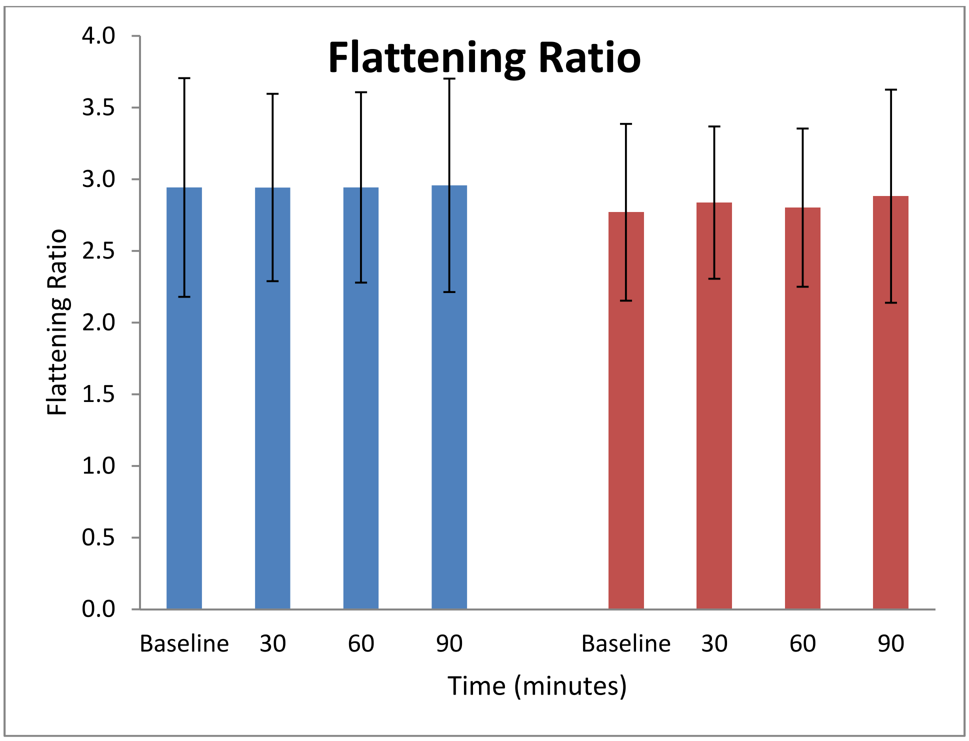


Figure 13. The flattening ratio at the pisiform level in dominant (blue) and non-dominant (red) hands, at the baseline, 30-minute, 60-minute, and 90-minute time points. Error bars represent standard deviations.

3.4.3 Wrist Postures

The average wrist flexion/extension angles, average wrist ulnar/radial deviations, average peak wrist flexion/extension angles (Figure 14), and average peak wrist ulnar/radial deviations were determined for the dominant side (Table 6). In addition, the flexion and adduction/abduction angles of three middle fingers were calculated (Figure 15).

Table 6. Average wrist flexion/extension (flexion is positive, extension is negative) and ulnar/radial deviation (radial deviation is positive, ulnar deviation is negative), average peak flexion, extension, and ulnar and radial deviation of the wrist during keyboarding

	Mean ± SD (degrees)	**Range (degrees)**
Average wrist flexion/extension	-25.4 ± 5.0	-47.3 – 4.6
Average wrist ulnar/radial deviation	-13.3 ± 7.7	-29.3 – 21.0
Average peak flexion	10.3 ± 4.6	2.7 – 17.4
Average peak extension	-34.2 ± 8.2	-47.4 – -14.5
Average peak ulnar deviation	-23.4 ± 9.4	-38.7 – -2.7
Average peak radial deviation	7.3 ± 6.3	0.4 – 21.6

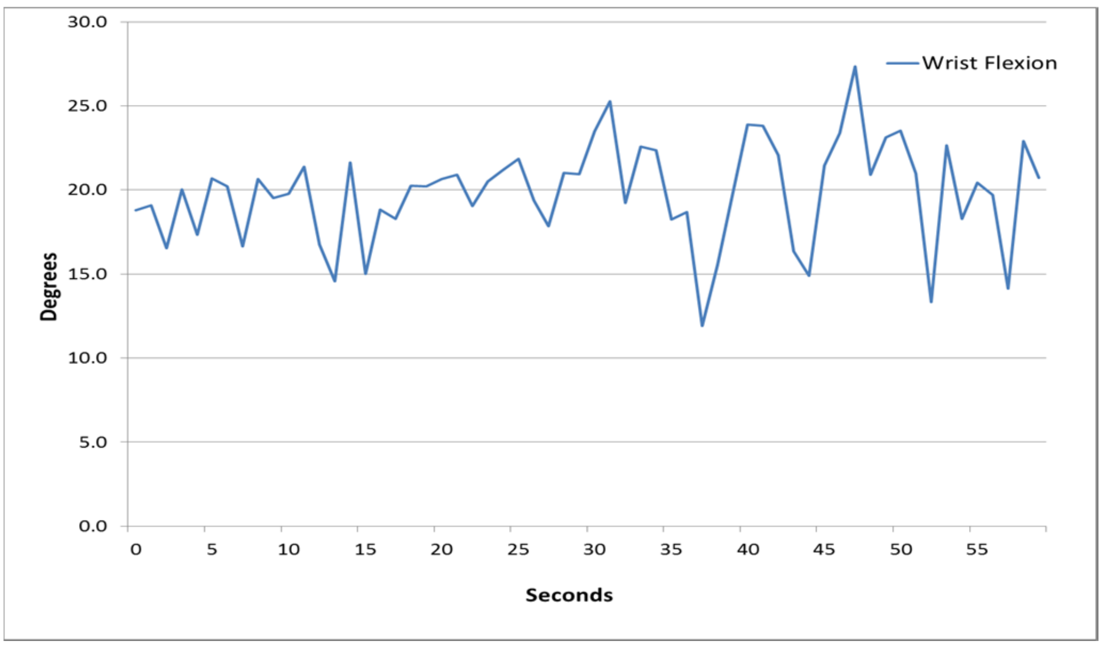


Figure 14. A representative graph depicting wrist flexion angles during a one-minute keyboarding task

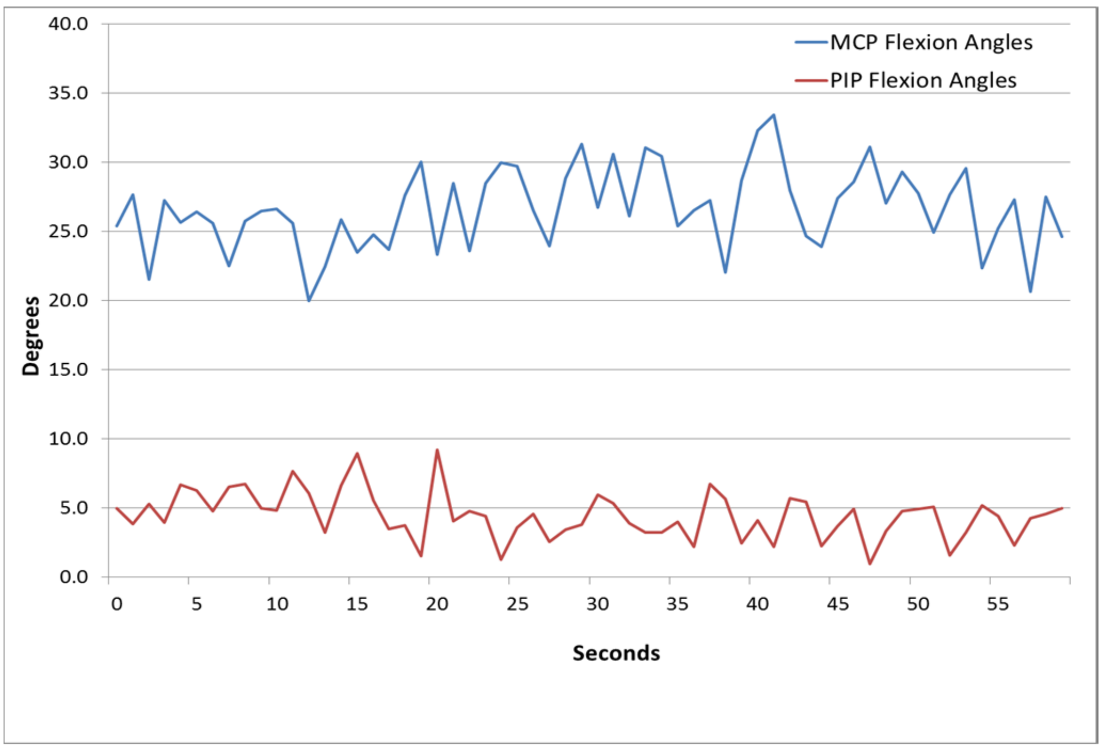


Figure 15. A representative graph demonstrating the flexion angles of the index finger during a one-minute keyboarding task

3.4.4 Keystroke Forces

Forces applied to the keys during typing were collected for the dominant hand using the ELF system (Figure 16). For the right-handed subjects, “U”, “I” and “O” keys were instrumented. These keys are commonly struck by the right index, middle and ring finger, respectively. For the subjects who were left-handed, forces applied to “W”, “E” and “T” keys were measured. Forces were collected over 4 one-minute periods and their peak and average values are presented in Table 7.

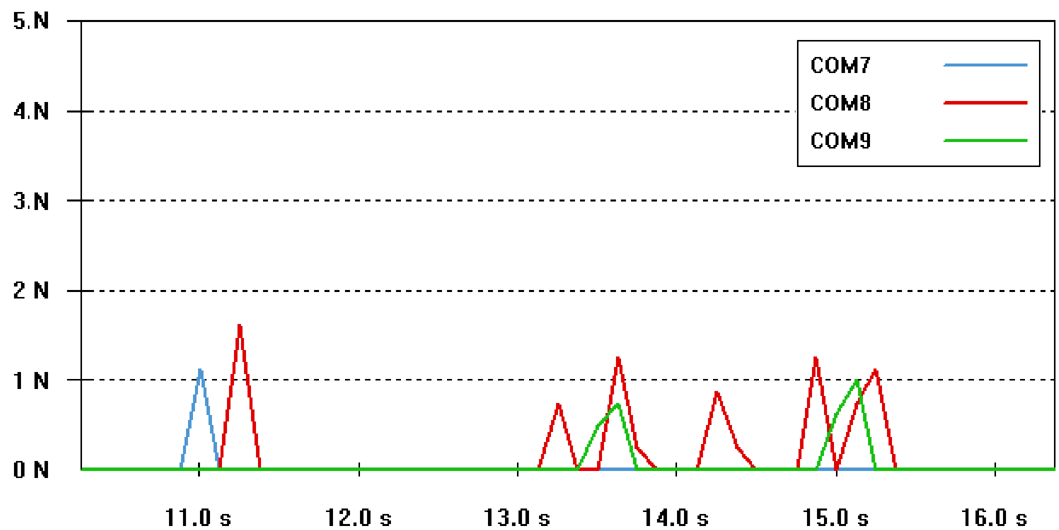


Figure 16. An exemplar screen capture of the ELF system showing three channels collecting data simultaneously

Table 7. Peak and average forces generated by the index, middle and ring fingers during keyboarding

		Forces by Index Finger Mean ± SD (N)	Forces by Middle Finger Mean ± SD (N)	Forces by Ring Finger Mean ± SD (N)
Male	Peak	2.54 ± 1.15	4.11 ± 2.95	2.13 ± 1.30
	Average	1.32 ± 0.71	1.28 ± 1.01	0.91 ± 0.38
Female	Peak	2.91 ± 1.06	3.16 ± 1.52	2.15 ± 0.74
	Average	1.39 ± 0.52	0.90 ± 0.26	0.90 ± 0.20
Overall	Peak	2.80 ± 1.30	3.50 ± 2.31	2.12 ± 1.01
	Average	1.38 ± 0.67	1.08 ± 0.74	0.90 ± 0.29

3.4.5 Linear Correlations

3.4.5.1 Correlation between the median nerve measures at the baseline and following the keyboarding task

Pearson correlations were performed to examine the associations between the median nerve variables at the three time points from the start of the keyboarding task and their corresponding baseline values. The results, summarized in Table 8, indicate that all three variables at each time point were significantly correlated to the respective baseline values.

Table 8. Coefficients of correlation between the baseline CSA, swelling ratio, and flattening ratio and their counterparts at three time points (p-values are shown in the parentheses)

	30-minute	60-minute	90-minute
Baseline Cross-sectional Area	0.892 (<0.001)	0.835 (<0.001)	0.867 (<0.001)
Baseline Swelling Ratio	0.690 (<0.001)	0.558 (<0.001)	0.424 (0.010)
Baseline Flattening Ratio	0.703 (<0.001)	0.640 (<0.001)	0.724 (<0.001)

3.4.5.2 Correlation between the median nerve measures and subject characteristics

The results of Pearson Correlations that tested correlation between the median nerve CSA, swelling ratio and flattening ratio and subject characteristics are tabulated in Table 9.

Table 9. Coefficients of correlation between subject characteristics and CSA, swelling ratio, and flattening ratio (p-values are shown in the parentheses)

		Gender	Age	BMI	Typing Speed	Wrist Circ.
CSA	Baseline	-0.252 (0.138)	0.071 (0.138)	0.347* (0.038)	0.130 (0.450)	0.426* (0.010)
	30-min	-0.093 (0.589)	-0.093 (0.589)	0.405* (0.014)	0.216 (0.207)	0.342* (0.041)
	60-min	-0.138 (0.423)	0.061 (0.722)	0.197 (0.249)	0.074 (0.669)	0.283 (0.094)
	90-min	-0.161 (0.349)	0.196 (0.252)	0.410* (0.013)	0.082 (0.634)	0.403* (0.015)
Swelling Ratio	Baseline	-0.158 (0.357)	-0.440* (0.007)	-0.057 (0.741)	0.161 (0.347)	0.126 (0.463)
	30-min	0.030 (0.862)	-0.268 (0.113)	0.008 (0.961)	0.247 (0.146)	0.112 (0.516)
	60-min	0.162 (0.346)	-0.386* (0.020)	-0.117 (0.496)	0.193 (0.259)	-0.088 (0.610)
	90-min	0.130 (0.449)	-0.023 (0.897)	-0.039 (0.819)	0.383* (0.021)	0.035 (0.839)
Flattening Ratio	Baseline	0.880 (0.610)	0.197 (0.610)	0.058 (0.739)	0.329* (0.050)	0.053 (0.761)
	30-min	-0.077 (0.657)	-0.082 (0.633)	0.128 (0.457)	0.138 (0.423)	0.159 (0.355)
	60-min	0.027 (0.877)	0.036 (0.836)	0.021 (0.904)	0.266 (0.123)	-0.025 (0.887)
	90-min	0.046 (0.791)	0.068 (0.693)	0.071 (0.682)	0.247 (0.146)	-0.045 (0.796)

* indicates significant correlation.

Our analyses demonstrated no significant correlation between acute changes in the median nerve (i.e., changes in the cross-sectional area, swelling ratio, and flattening ratio) and subjects' gender. The results, however, revealed significant positive correlation between the CSA and subjects' BMI and wrist circumference, and positive correlation between the SR and FR and subjects' typing speed. Furthermore, significant negative correlations between the swelling ratio and subjects' age were observed (Table 9). The results also suggested that the wrist circumference, gender and BMI could be confounding factors.

3.4.5.3 Correlation between the median nerve measures and wrist biomechanical factors

Correlation between acute changes in the median nerve cross-sectional area, swelling ratio and flattening ratio and wrist biomechanical variables of the dominant side were tested by Pearson Correlation. Table 9 shows the results of this analysis for the median nerve measures and main wrist postures (i.e., peak flexion and peak ulnar deviation) and average keystroke force. The results indicate that the only significant correlation between the ultrasonographic measures of median nerve and the wrist positions during keyboarding was a positive correlation between the swelling ratio of the nerve after 30 minutes of keyboarding and peak ulnar deviation ($p = 0.047$), and a positive correlation between the baseline flattening ratio and peak wrist flexion ($p = 0.046$). The changes in the cross-sectional area and swelling ratio of the dominant median nerve were also tested for any possible correlation with peak and average keystroke reaction forces during keyboarding (Table 10 presents the results of average keystroke forces). None of the returned coefficients of correlation, listed in the table, was statistically significant.

Table 10. Coefficients of correlation between the median nerve CSA, swelling ratio, and flattening ratio and wrist biomechanical variables (peak wrist flexion, peak wrist ulnar deviation, and average keystroke force). P-values were shown in the parentheses.

		Peak Wrist Flexion (°)	**Peak Wrist Ulnar Deviation (°)**	**Average Force (N)**
CSA	Baseline	0.189 (0.269)	-0.032 (0.854)	0.055 (0.751)
	30-min	0.090 (0.603)	0.005 (0.977)	-0.021 (0.902)
	60-min	0.061 (0.725)	-0.002 (0.993)	0.080 (0.641)
	90-min	0.210 (0.219)	-0.101 (0.560)	0.132 (0.444)
Swelling Ratio	Baseline	0.033 (0.848)	0.289 (0.087)	-0.138 (0.422)
	30-min	-0.019 (0.913)	0.333* (0.047)	0.057 (0.741)
	60-min	-0.294 (0.082)	0.295 (0.081)	-0.118 (0.494)
	90-min	-0.146 (0.396)	0.095 (0.582)	-0.073 (0.672)
Flattening Ratio	Baseline	0.125 (0.468)	0.040 (0.815)	0.284 (0.093)
	30-min	0.335* (0.046)	-0.091 (0.597)	0.210 (0.219)
	60-min	0.277 (0.108)	0.083 (0.637)	0.077 (0.659)
	90-min	0.132 (0.442)	0.006 (0.970)	0.106 (0.540)

* indicates significant correlation.

3.4.5.4 Correlation between the Acute Changes in Median Nerve Measures and Subject Characteristics

The results of Pearson Correlations that tested correlation between the acute changes in median nerve CSA (ΔCSA), swelling ratio (ΔSR), and flattening ratio (ΔFR) and subject characteristics are tabulated in Table 11. These results indicate that acute changes in swelling ratio at 60-minute time point had significant positive correlations with subjects' age.

Table 11. Coefficients of correlation between subject characteristics and ΔCSA, ΔSR, and ΔFR (p-values are shown in the parentheses)

		Gender	Age	BMI	Typing Speed	Wrist Circ.
ΔCSA	30-min	0.307 (0.069)	0.066 (0.700)	0.192 (0.262)	0.194 (0.258)	-0.082 (0.633)
	60-min	0.251 (0.140)	-0.047 (0.785)	-0.322 (0.055)	-0.079 (0.647)	-0.294 (0.081)
ΔSR	30-min	0.239 (0.160)	0.192 (0.263)	0.082 (0.634)	0.123 (0.475)	-0.014 (0.938)
	60-min	0.259 (0.127)	0.376* (0.024)	-0.052 (0.764)	0.017 (0.923)	-0.216 (0.206)
ΔFR	30-min	-0.205 (0.230)	-0.158 (0.357)	0.077 (0.654)	-0.270 (0.111)	0.105 (0.543)
	60-min	-0.089 (0.604)	-0.209 (0.220)	-0.036 (0.837)	-0.076 (0.658)	-0.085 (0.624)

3.4.5.5 Correlation between the Acute Changes in Median Nerve Measures and Wrist Biomechanical Factors

Correlation between acute changes in the median nerve cross-sectional area (ΔCSA), swelling ratio (ΔSR), and flattening ratio (ΔFR) and wrist biomechanical variables of the dominant side were tested by Pearson Correlation. Table 12 shows the results of this analysis for the changes in median nerve measures and main wrist postures (i.e., flexion and ulnar deviation) and average keystroke force. The change in swelling ratio at 60-minute time point demonstrated a significant negative correlation with the peak wrist flexion.

Table 12. Coefficients of correlation between the acute changes in median nerve CSA (ΔCSA), swelling ratio (ΔSR), and flattening ratio (ΔFR) and wrist biomechanical variables (peak wrist flexion, peak wrist ulnar deviation, and average keystroke force). P-values were shown in the parentheses.

		Peak Wrist Flexion (°)	**Peak Wrist Ulnar Deviation (°)**	**Average Force (N)**
ΔCSA	30-min	-0.144 (0.402)	0.094 (0.588)	-0.143 (0.407)
	60-min	-0.275 (0.104)	0.055 (0.748)	0.045 (0.796)
ΔSR	30-min	-0.076 (0.661)	0.080 (0.642)	0.240 (0.159)
	60-min	-0.375* (0.024)	-0.029 (0.868)	0.018 (0.917)
ΔFR	30-min	0.204 (0.234)	-0.144 (0.401)	-0.112 (0.516)
	60-min	0.128 (0.457)	0.026 (0.880)	-0.252 (0.139)

3.4.6 Linear Regression Models for the Median Nerve Measures as Dependent Variables

3.4.6.1 Linear regression models with subject characteristics as independent variables

Based on the results of multiple linear regression models (Equations 1A, 1B, and 1C), only the baseline values appeared to account for the ability to predict the median nerve measures at other time points. No subject characteristic was found to be a significant contributor. Wrist circumference, which was previously included in the correlation analyses, was excluded due to possible confounding effects. All three models demonstrated a relatively high R-squared value (Table 13) and power of performed tests with alpha = 0.050 was 1.00.

A. CSA_30 minute = -2.020 + (1.017 * CSA_Baseline) + (0.569 * Gender) + (0.00177 * age) + (0.0588 * BMI) + (0.00921 * Typing Speed)

CSA_60 minute = 2.988 + (0.901 * CSA_Baseline) + (0.348 * Gender) + (0.00116 * age) - (0.0367 * BMI) - (0.0129 * Typing Speed)

B. SR_30 minute = 0.0922 + (0.817 * SR_Baseline) + (0.0408 * Gender) - (0.000157 * age) + (0.00264 * BMI) + (0.00135 * Typing Speed)

SR_60 minute = 0.653 + (0.507 * SR_Baseline) + (0.0715 * Gender) - (0.00514 * age) - (0.000753 * BMI) + (0.00103 * Typing Speed)

C. FR_30 minute = 1.218 + (0.630 * FR_Baseline) - (0.126 * Gender) - (0.00372 * age) + (0.00964 * BMI) - (0.00367 * Typing Speed)

FR_60 minute = 1.449 + (0.551 * FR_Baseline) - (0.0942 * Gender) - (0.0110 * age) - (0.00600 * BMI) + (0.00689 * Typing Speed)

Equations 1. Multiple linear regression models that incorporated baseline values and subjects characteristics to predict values of the median nerve CSA (A), swelling ratio (B), and flattening ratio (C) following the keyboarding

Table 13. P-value for each variable in the linear regression models presented above and R-squared values for each model.

		R^2	Constant	Baseline	Gender	Age	BMI	Speed
Cross-sectional Area	**30**	0.831	0.154	<0.001	0.127	0.943	0.122	0.574
	60	0.716	0.061	<0.001	0.395	0.967	0.378	0.480
Swelling Ratio	**30**	0.509	0.732	<0.001	0.403	0.967	0.584	0.558
	60	0.414	0.018	0.007	0.140	0.174	0.873	0.648
Flattening Ratio	**30**	0.521	0.080	<0.001	0.493	0.776	0.604	0.674
	60	0.429	0.070	<0.001	0.664	0.465	0.787	0.501

3.4.6.2 Linear regression models with biomechanical factors as independent variables

When combinations of biomechanical variables were used to construct the multiple linear regression models, the baseline values appeared to account for the ability to predict the median nerve measures in all the models (Equations 2A, 2B, and 2C). The only biomechanical factor that was a significant contributor in predicting the median nerve swelling ratio and flattening ratio was the peak wrist flexion (Table 14). All the models demonstrated a relatively high R-squared value (Table 14) and power of performed tests with alpha = 0.050 was 1.00.

A. $$CSA\_30\ minute = 0.608 + (1.061 * CSA\_Baseline) - (0.0170 * Peak\ wrist\ flexion) + (0.0126 * Peak\ wrist\ ulnar\ deviation) - (0.152 * Average\ Force\ (N))$$

$$CSA\_60\ minute = 2.400 + (0.852 * CSA\_Baseline) - (0.0202 * Peak\ wrist\ flexion) + (0.00332 * Peak\ wrist\ ulnar\ deviation) + (0.0656 * Average\ Force\ (N))$$

B. $$SR\_30\ minute = 0.201 + (0.798 * SR\_Baseline) - (0.00107 * Peak\ wrist\ flexion) + (0.00163 * Peak\ wrist\ ulnar\ deviation) + (0.0190 * Average\ Force\ (N))$$

$$SR\_60\ minute = 0.675 + (0.532 * SR\_Baseline) - (0.00487 * Peak\ wrist\ flexion) + (0.00264 * Peak\ wrist\ ulnar\ deviation) - (0.00874 * Average\ Force\ (N))$$

C. $$FR\_30\ minute = 0.849 + (0.572 * FR\_Baseline) + (0.0174 * Peak\ wrist\ flexion) - (0.00885 * Peak\ wrist\ ulnar\ deviation) + (0.0188 * Average\ Force\ (N))$$

$$FR\_60\ minute = 0.946 + (0.570 * FR\_Baseline) + (0.0149 * Peak\ wrist\ flexion) + (0.00678 * Peak\ wrist\ ulnar\ deviation) - (0.0939 * Average\ Force\ (N))$$

Equations 2. Multiple linear regression models that incorporated baseline values and biomechanical variables to predict values of the median nerve CSA (A), swelling ratio (B), and flattening ratio (C) following the keyboarding task

Table 14. P-value for each variable in the linear regression models presented above and R-squared values for each model.

		R^2	Constant	Baseline	Peak Wrist Flexion	Peak Wrist Ulnar Deviation	Average Force
CSA	30	0.809	0.597	<0.001	0.347	0.459	0.338
	60	0.709	0.055	<0.001	0.291	0.853	0.694
SR	30	0.512	0.279	<0.001	0.630	0.475	0.354
	60	0.436	<0.001	0.002	0.029	0.233	0.658
FR	30	0.574	0.049	<0.001	0.040	0.262	0.804
	60	0.473	0.065	<0.001	0.128	0.467	0.284

3.4.6.3 Linear regression models with combination of subject characteristics and biomechanical factors as independent variables

The results of multiple linear regression models in which combinations of subject characteristics and biomechanical factors were used (Equations 3A, 3B, and 3C) indicated that the baseline values constantly appeared to be able to account for the ability to predict the median nerve measures. In addition, the peak wrist flexion had a p-value of 0.018 in the flattening ratio regression model. The complete outcomes of the multiple linear regression models are presented in Appendix A.

A. CSA_30 minute = -2.184 + (1.020 * CSA_Baseline) + (0.410 * Gender) + (0.0195 * age) + (0.0655 * BMI) + (0.00924 * Typing Speed) - (0.0155 * Peak wrist flexion) + (0.0220 * Peak wrist ulnar deviation) - (0.142 * Average Force (N))

CSA_60 minute = 3.061 + (0.907 * CSA_Baseline) + (0.273 * Gender) + (0.00614 * age) - (0.0341 * BMI) - (0.0131 * Typing Speed) - (0.0173 * Peak wrist flexion) + (0.000741 * Peak wrist ulnar deviation) + (0.0700 * Average Force (N))

B. SR_30 minute = -0.0940 + (0.819 * SR_Baseline) + (0.0373 * Gender) + (0.00139 * age) + (0.00297 * BMI) + (0.00185 * Typing Speed) - (0.000671 * Peak wrist flexion) + (0.00227 * Peak wrist ulnar deviation) + (0.0222 * Average Force (N))

SR_60 minute = 0.672 + (0.498 * SR_Baseline) + (0.0452 * Gender) - (0.00297 * age) + (0.000306 * BMI) + (0.00105 * Typing Speed) - (0.00373 * Peak wrist flexion) + (0.00204 * Peak wrist ulnar deviation) - (0.00492 * Average Force (N))

C. FR_30 minute = 1.423 + (0.623 * FR_Baseline) + (0.00305 * Gender) - (0.0168 * age) + (0.00401 * BMI) - (0.00408 * Typing Speed) + (0.0180 * Peak wrist flexion) - (0.0137 * Peak wrist ulnar deviation) + (0.0120 * Average Force (N))

FR_60 minute = 1.097 + (0.543 * FR_Baseline) - (0.0484 * Gender) - (0.0146 * age) - (0.0128 * BMI) + (0.00933 * Typing Speed) + (0.0193 * Peak wrist flexion) + (0.00480 * Peak wrist ulnar deviation) - (0.0711 * Average Force (N))

Equations 3. Multiple linear regression models that combine the baseline values, subject characteristics and biomechanical variables to predict values of the median nerve CSA (A), swelling ratio (B), and flattening ratio (C) following the keyboarding task

3.5 DISCUSSION

3.5.1 Acute Changes in the Ultrasonographic Measures of the Median Nerve

The study presented in Chapter I has previously demonstrated that a continuous keyboarding task could cause acute changes in the ultrasonographic measures of the median nerve. Particularly, 60 minutes of computer keyboarding resulted in significant increase in the cross-sectional area and swelling ratio of the median nerve. The results of the current study were consistent with the previous findings. The median nerve cross-sectional area at the pisiform level and swelling ratio increased significantly in both dominant and non-dominant wrists after 30 minutes of continuous keyboarding when compared to those at baseline. These two ultrasonographic measures were also significantly higher after 60 minutes of keyboarding compared to the baseline values.

One major difference between the results of current study and those of the pilot study was that although median nerve cross-sectional area and swelling ratio demonstrated an increase with respect to baseline, they became significantly greater only after the 60-minute keyboarding task was completed. In the current study, however, both cross-sectional area and swelling ratio showed significant increases at 30-minute, as well as 60-minute time point. Another difference observed was that the pilot study demonstrated an increase in the cross-sectional area of both sides, while the swelling ratio was significantly higher only on the dominant side. Our current findings show that not only cross-sectional area was statistically larger in both dominant and non-dominant hands at the end of the keyboarding task, but the swelling ratio became significantly different in both hands after 30 and 60 minutes of keyboarding. It seems that a larger sample size helped acute changes in the median nerve become more “measurable.”

One further step that was added to the current study was to investigate additional changes in the median nerve characteristics that could have occurred after a period of rest following the keyboarding task. The findings of our pilot study suggested that the changes in the median nerve measures were rather dose-dependent; therefore, we hypothesized that the acute changes in the median nerve that were caused by prolonged keyboarding would reduce upon resting the upper extremities. As such, a 30-minute resting period during which subjects deferred to perform any manual activity was added to the research protocol. This was followed by a final ultrasound examination. Our results indicate that both cross-sectional area and swelling ratio, which increased significantly by completion of the continuous keyboarding task, decreased after 30 minutes of manual rest. In fact, the cross-sectional area and swelling ratio at the 90-minute time point (i.e., at the end of resting period) were not statistically different from those at the baseline.

Similar to the previous study, the flattening ratio did not change significantly as a result of prolonged keyboarding. It appears that, although the median nerve cross-sectional area at the pisiform level increased as a result of keyboarding, which eventually caused greater swelling ratio, the two-dimensional nerve enlargement occurred in a proportional way. In other words, the increment of the long axis and short axis of the median nerve were rather proportional; therefore, the nerve flattening ratio, which is defined as nerve width divided by nerve height, remained relatively unchanged (see Figure 17).

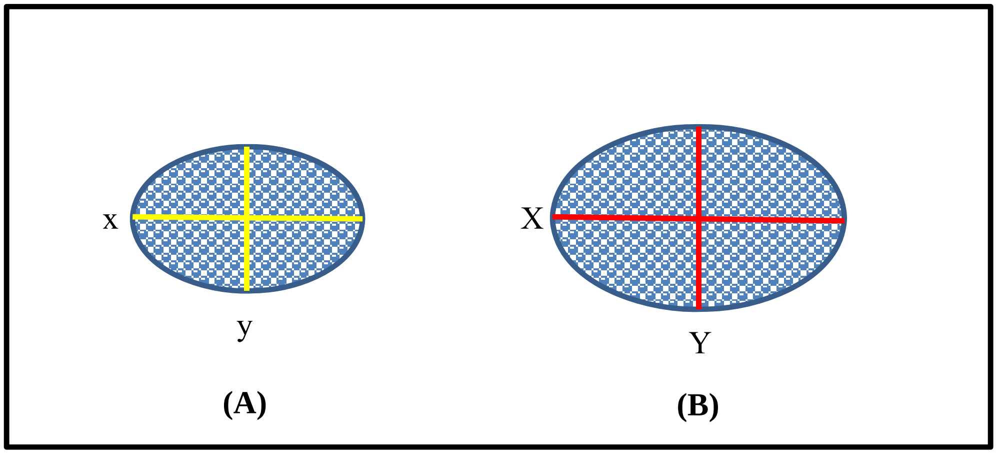


Figure 17. A schematic of the cross-sectional area of the median nerve at the pisiform level, depicting the nerve prior to, (A), and after the prolonged keyboarding task, (B). While the cross-sectional area of the nerve show an increase as a result of keyboarding compared to the baseline, the flattening ratio remained relatively unchanged, since the nerve width divided by nerve height at the baseline (i.e., x/y) is approximately equal to the same ratio at the end of keyboarding task (i.e., X/Y)

The results of the correlation analyses indicated that the changes in median nerve measures were significantly correlated to the baseline values for the corresponding variables. While this finding was not unpredictable, it was important to establish such a correlation prior to constructing the regression models. This would help minimize the effects of individual differences in the subjects' median nerve size and shape prior to the keyboarding task. Furthermore, identifying this correlation was significant as we aim to lay a foundation for methodology that can be used in future studies that investigate changes in the median nerve of patients or symptomatic individuals. Investigators need to acknowledge the role of baseline values as they appear to be the most significant contributor to potential changes in the median nerve upon manual activities.

3.5.2 Significance of Subject Characteristics

Previously, we reported a significant positive correlation between the median nerve cross-sectional area and subject age in our pilot study. This finding supported epidemiological studies that have shown the prevalence of carpal tunnel syndrome increases by age.[4,70] The results of our current study also demonstrated significant positive correlation between the median nerve swelling ratio and subjects' age. In addition, the BMI was found to be significantly positively correlated with the CSA; a finding that resonates what has been reported in the literature.

Our previous study showed statistically similar typing speed in male and female participants. In this study, we observed a significant difference between male and female subjects' typing speed. This finding also had significant correlation with changes in the nerve swelling ratio and flattening ratio as a result of keyboarding.

Taking anthropometric measurements was another additional step that was performed during the general data collection phase. These measurements were used to construct a biomechanical model for estimating the amount of tendon travel (see Chapter III). Although biomechanical literature does not support the idea that the size of the wrist, hence the diameter of the carpal tunnel may play a role in development of the nerve entrapment, wrist circumference measurements were made. In this study, we found significant difference between male and female subjects' wrist circumference. Furthermore, a significant correlation was found between the subjects' wrist circumference and cross-sectional area of the non-dominant median nerve. The clinical significance of this finding is yet to be determined.

3.5.3 Wrist Biomechanics and Changes in the Ultrasound Measures of Median Nerve

Many research studies have focused on the associations between upper extremity postures and musculoskeletal disorders, including pain and discomfort (see Introduction). Abnormal postures are suggested to put increased forces such as friction and shear on tendons and tendon sheathes.[13,74,107,108] In particular, forearm pronation, wrist extension, wrist flexion, and ulnar deviation also increase carpal tunnel pressure,[55,109,110] which has been hypothesized to increase the risk for tendonitis and carpal tunnel syndrome.[83]

As outlined in our specific aims, upon finding changes in the median nerve ultrasound measurements, we investigated whether hand and wrist biomechanical variables could be related to these changes. In particular, we were interested in certain wrist angles, as well as keystroke reaction forces collected during the keyboarding task. Correlation analyses were used to find significant correlation between the median nerve measures and wrist biomechanical parameters, which demonstrated significant positive correlation between the swelling ratio and peak wrist ulnar deviation and between the flattening ratio and peak wrist flexion. The former finding supported our second hypothesis, but the latter was in contrast to what we hypothesized. As stated in Section 3.2.2, we anticipated that the wrist extension to be significantly correlated to the changes in median nerve measures.

It was also hypothesized that the average resultant forces at the wrist would have a significant correlation with the observed changes in the median nerve. We assumed that the keystroke reaction forces would result in loads and/or moments at the wrist joint, which could be calculated using an inverse dynamic model. While this approach has become a common and reliable methodology in evaluating forces and movements of the upper and lower extremities, it was proved to be limited by many restraints for this application. First of all, our data did not include angles between the fingers and the keyboard keys. Second, the mass and moment of inertia for the phalanges were not available in the current literature/textbooks. Furthermore, assuming that some major assumptions could be made to consider some of the unknowns as "negligible," the results would be very sensitive to the paths chosen for the tendons, as the moment arms in question are very small. As a result, we decided to evaluate the "raw" forces, meaning the keystroke reaction forces that were directly collected during the keyboarding task. Our results, however, revealed no significant correlation between these forces and the median nerve changes. This finding was not unpredictable; the studies that investigated the effects of forceful tasks on median nerve pathophysiology found forces of one order of magnitude higher than that was observed in our study (i.e., tens of Ns) to be correlated to the nerve injury. It is worth mentioning that our kinetics data were collected at 8 Hz (the only available frequency for recording data for one minute), which is far below the desired sampling frequency for this study since the sampling frequency for our kinematics data was 60 Hz. This discrepancy could have adversely affected our results and caused underestimating "peak" forces over the period of data collection.

In addition to the correlation models, we constructed multiple linear regression models that utilized the baseline value and combination of independent variable (i.e., subject characteristics and biomechanical factors) to predict the changes in the median nerve cross-sectional area, swelling ratio and flattening ratio as a result of prolonged keyboarding. While the results of these models constantly demonstrated highly significant relationship between each dependent variable and its baseline counterpart, they further emphasized the importance of wrist biomechanics in predicting the acute changes in median nerve measures. In particular, the peak wrist flexion was found to be a significant factor to contribute to the observed changes. Other independent variables did not reveal any significant role in the regression models. However, this could be interpreted as a manifestation of multifactorial nature of the median nerve pathophysiology, where all said variables may play a relatively small part in the process, but together result in acute changes in the nerve size and shape. Nevertheless, the regression models constantly indicated a strong relationship between the nerve measures and their baseline values throughout the analysis. This finding will help future studies design and apply a rather modified methodology for symptomatic subjects by taking to account that patients with median nerve pathology may demonstrate an altered "baseline."

3.5.4 Limitations

The main purpose of this study was to establish a baseline understanding of keyboarding biomechanics in healthy subjects. By testing people with no signs of CTS we are selecting a population that may be at less risk to injury. We believe this is needed to remove clinical variability from the study. However, by not including CTS (or other median neuropathy) patients, we missed the opportunity to make comparison between our findings and potentially different results in the individuals with median nerve disorders. Furthermore, including only one group of subjects (i.e., healthy participants) was considered a flaw in our study design, as we did not have any control group. Ideally, subjects in the control group would do nothing manually during a period of time equivalent to the periods where the other participants would keyboard. This would allow investigating any possible changes in the median nerve measures in the absence of a manual activity such as keyboarding, and the data could be used to perform more comprehensive statistical analyses.

In this study, we did not attempt to recreate each subject's work set up as we believe attempting to recreate the workstation would add variability to the experiment. As discussed before, research has shown that there is great variety in preferred postures/styles among different keyboard users that appear to be related to the physical characteristics of the workstation.[109,110] Evaluating the potential effects of physical setup of the workstation on the median nerve measures must be included in future studies.

The usage of computer mouse during the keyboarding task was purposefully eliminated. Working with the mouse is a major component of computer use, and frequency, duration and style of using a mouse may be important factors that can affect wrist posture and result in median nerve injury over time. Fogleman and Brogmus reported that, due to the adoption of the graphical user interfaces, pointing devices (e.g., computer mouse, trackballs) are present in every office environment.[111] The use of the mouse has been reported to account for almost 60% of total time in most applications[112-114] with a maximum level of usage of 65–70% in drawing applications.[115] The lateral position of the mouse, due to the original workstation design that took into consideration only the keyboard, causing the abduction of the arm[116,117] with the wrist ulnar deviated,[118] extended, high muscular tension and fatigue. These, plus the prolonged awkward postures have been reported as risk factors for CTS.[119,120] This study focused on the keyboarding aspect only and the role of mouse or other pointing devices will be the subject of future studies.

Biomechanical data were collected only from the dominant side, while we examined both sides through the clinical ultrasound examinations. It has been suggested that keyboarding is not a symmetrical task.[88] Dvorak suggested that a conventional QWERTY keyboard causes overloading of the "weaker" left hand in a right-handed person.[121] Many studies have concluded similar or additional outcomes since then and reported differences between left and right forearms and wrists during keyboarding.[61,62,122,123] As such, reporting biomechanical data for only the dominant side is another limitation in this study that needs to be addressed in future studies.

Furthermore, limited kinetics data (i.e., keystroke forces collected at 8 Hz) prevented our study from thoroughly investigating the effects of reaction forces applied to fingers during the keyboarding task on the median nerve measures. While the range of collected data was in agreement with the current literature, we suspect that our study did not necessarily record all the forces applied to the fingers, and peak forces especially could have been missed out. Finally, the lack of anthropometric measurements of the MCP and PIP joints for each participant prevented our regression models from being individually-tailored for each subject. By adding such a simple measurement to future studies, one would speculate that a more subject-specific calculation could improve the biomechanical model and further elucidate the relationship between the tendon travel and acute changes in the median nerve characteristics.

Finally, while all multiple regression models exhibited a power of 1.00 with performed tests at alpha = 0.050, stability of the models is not clear. As a "rule of thumb," larger samples are better than smaller samples (all other things being equal) because larger samples tend to minimize the probability of errors, maximize the accuracy of population estimates, and increase the generalizability of the results.[124] Unfortunately, there are few sample size guidelines for researchers using regression models. It has been suggested that the repeated measure studies require even relatively lower subject-to-variable ratio; however, there was minimal empirical evidence to support this. Obviously, a greater sample size would provide more stable models and the most valid conclusion regarding sample size would be that more is always better.[124]

3.6 CONCLUSIONS

Using ultrasonography we were able to detect acute changes in the median nerve following a one-hour continuous keyboarding assignment. The median nerve cross-sectional area and swelling ratio were significantly higher after 30 and 60 minutes of keyboarding. These results were in agreement and supportive of the findings of our previous study. In addition, a 30-minute resting period followed by an additional round of ultrasound examination demonstrated that the observed changes in the cross-sectional area and swelling ratio of the median nerve decreased drastically upon resting the upper extremities.

The correlation analyses revealed that the observed changes in the median nerve ultrasound measures were significantly correlated with the subject characteristics (i.e., age, BMI, typing speed, and wrist circumference), and also with average peak wrist flexion and ulnar deviation in the dominant hand. These findings emphasized the importance of certain physical characteristics of the typist, as well as harmful habits, such as extreme postures during keyboarding, in the pathophysiology of the median nerve injury. Moreover, our regression models may provide future investigations with a tool that can help predict median nerve behavior as a result of manual task. This information provides insight into understanding how combination of several physical and mechanical factors can contribute to development of disorders such carpal tunnel syndrome. Long-term studies, however, are required to thoroughly investigate the role and importance of any of these personal and/or environmental contributors.

4.0 CHAPTER III

THE RELATION BETWEEN TENDON TRAVEL AND ACUTE CHANGES OF THE MEDIAN NERVE DURING KEYBOARDING

4.1 INTRODUCTION

Previously we demonstrated that a continuous one-hour keyboarding assignment caused acute changes in the ultrasonographic measures of the median nerve. We also attempted to correlate these changes to a variety of contributing factors, such as individual features, as well certain biomechanical variables. Furthermore, we quantified the amount of tendon travel as a function of keyboarding and investigate the effects of tendon travel on the median nerve measures.

Carpal tunnel is a narrow pathway on the palm side of the wrist. It contains the median nerve and the flexor tendons that bend the fingers. The flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS) muscles of the forearm are two major finger flexor muscles and are the only muscles involved in flexion of all four fingers.[125] Tendons of both the FDS and FDP are contained within a common sheath passing through the carpal canal. During keyboarding, the adjacent tendons are sliding one against the other and against the median nerve. Movement of the flexor tendons within the common sheath has been used as an indicator of biomechanical stress by several researchers.[100,126-129]

4.1.1 Tendon Travel and Flexor Tenosynovium Thickening

Many authors[126,127] have reported that the nerve is compressed by thickening of the flexor tendon sheaths. In so many as 87% of the carpal tunnel syndrome (CTS) cases, Yamaguchi et al.[126] found greater fibrosis and edema in the tendon sheaths compared with controls. Moore et al.[128] used tendon excursion as one of the indicators of a repetitive and forceful task using a hand tool. Wells et al.[129] compared the amount of tendon travel for industrial workers and data entry clerks. Sommerich quantified the biomechanics of typing for 25 experienced computer users in three different occupational groups.[100] The average tendon travel, normalized to 1 hour of continuous typing, ranged from 30 to 59 m/h for the three groups.

Researchers hypothesize that friction develops as a result of the repetitive sliding of tendons within their sheaths during the performance of highly repetitive activities such as keyboarding. This friction may contribute to disorders of the tendons, their sheaths, or adjacent nerves.[5,7,130] Goldstein et al.[13] demonstrated a traction effect in the flexor tendons within the carpal canal, and tendon blood flow has been shown to decrease as tendon tension increases.[131] It has been found that carpal tunnel syndrome patients experience a thickening of the synovial sheath which results in abnormally high carpal tunnel pressure.[132] This pressure may interfere with nerve gliding, obstruct venous outflow, and promote edema formation. These factors perpetuate carpal tunnel collapse and consequently damage the median nerve. In one study,[133] MRIs in 14 subjects, half with CTS, were taken to compare groups in the ratio of carpal tunnel contents to carpal tunnel volume (CTC/CTV). Individuals with CTS had high CTC/CTV volumes. Although the MRI study did not specifically address tendon hypertrophy, one cause of an increase in the CTC/CTV ratio would be hypertrophy of the flexor tendons.

In a separate study, Pierre-Jerome found swelling of the tendon sheath in 77% of hands operated on for CTS.[134] In 1959, Tanzer described a tenosynovitis of the flexor tendons seen during surgery in cases of known CTS.[101] Gross et al. performed a histologic study of on 44 patients, 36 with CTS.[135] In this study, tenosynovium was biopsied at the time of surgery from the flexor digitorum profundus tendon. He found marked collagen degeneration in the tendons of individuals with CTS. Schuind noted fibrous hypertrophy in 21 individuals with CTS.[108]

4.1.2 Motivation

In summary, a relationship between CTS and tendon or synovial hypertrophy has been established and is likely a cause of increased pressure in the carpal canal. Many researchers have speculated as to the cause of this hypertrophy. Muscle activity of the flexors and repetitive tendon travel have been considered as the two main theories to explain hypertrophy. In this study, we focus on tendon travel as one of the biomechanical factors contributing to development of the carpal tunnel syndrome. Specifically, we adopt and modify a mathematical model of finger flexor tendons in which we can integrate individual anthropometric measurements and obtain an estimate of tendon displacement as a function of fingers and wrist angles during keyboarding. Furthermore, we investigate the correlation between the calculated tendon travel and acute changes in the median nerve ultrasound measures as a result of continuous keyboarding.

4.2 METHODS

4.2.1 Background

The tendon-joint displacement relationships are determined by the spatial relationships between the tendons and the joints. Landsmeer appeared to be the first to describe three different models of tendon-joint displacement.[136] Although several investigators have developed biomechanical models of finger flexor tendon displacements during pinching or gripping exertions of hands,[137-140] Landsmeer's models remains one of the most comprehensive set of models to date. In 1978, Armstrong and Chaffin used various-sized cadaver hands to statistically evaluate the Landsmeer models.[141] They included the effects of hand and wrist anthropometry for the first time. The results indicate that the tendons displace with respect to joint positions as described by the Landsmeer model in which the tendon is depicted as sliding over the curved articular surface of the proximal bone of the joint. They found that joint thickness effects modify the parameters in the model and developed an empirical prediction model of the anthropometric effects. Further, the tendon displacements for various wrist orientations were expressed empirically (Figure 18).

While models developed by Armstrong and Chaffin were shown to be consistent with expected anatomical considerations, and were subsequently used for a variety of applications,[101,142,143] it took investigators approximately 20 years to apply this methodology to keyboarding tasks. In 2000, Nelson, Treaster, and Marras, conducted two studies in which they calculated tendon travel as a function of the keyboard design, standardized to unit time.[144,145] They used the earlier models by Armstrong and Chaffin and their regression equations to calculate tendon travel for the FDP and FDS.

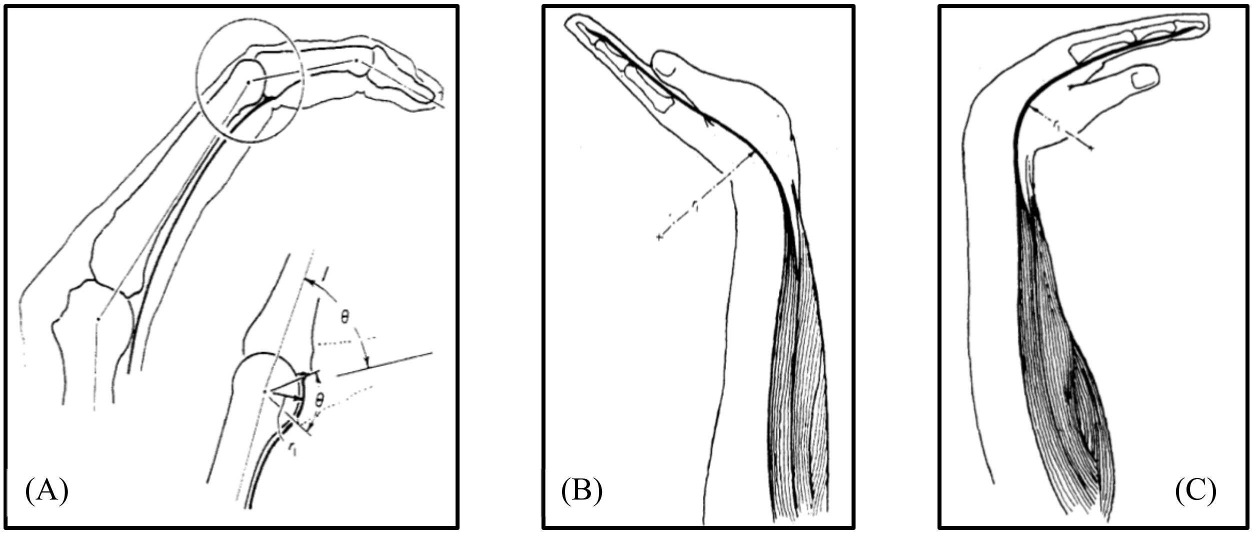


Figure 18. Copies of the schematics from Armstrong and Chaffin classic article[141] depicting the effects of finger flexion (A) and wrist extension (B) and flexion (C) on tendon displacement

A study by Goodman and Choueka examined basic tendon biomechanics, the anatomy and mechanics of digital flexor tendons, and the digital flexor pulley system.[146] This article discussed the various models that have tried to simulate the motion of the flexor tendons and several testing modalities that have been used. Thompson and Giurintano developed a multi-joint model based on Armstrong's work.[147] They modified the original model based on the idea that as each point on a phalanx is moved, its new position can be calculated by a transformation matrix in three dimensions. The tendon's course is described by a combination of multiple elements, including straight segments inside pulleys, curved segments between pulleys, and divergent segments such as the insertion of the FDS. Several other models have combined kinematic, computer, and radiographic modalities to simulate forces and stresses on the flexors and other forearm muscles.[148-150] Fowler and Nicol created a model using MRI to obtain moment arms and tendon lines of action in three dimensions.[150]

4.2.2 Biomechanical Model

In order to calculate tendon travel during keyboarding, the modified Armstrong and Chaffin model which was previously developed and tested for similar applications[144,145] was used. Although this model was not the most recent biomechanical model of hand and fingers to estimate tendon travel, it is one of the most comprehensive ones to date. This model allows calculating tendon excursion as a function of not only joint angles, but specific geometrical variables of the hand and fingers. It also takes wrist angles into account as well as the metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) angles. This model is applicable to both FDP and FDS tendons, and has been tested to determine if it could account for all differences among tendon-joint displacement relationships of different hands and fingers. In fact, it was proved to account for 97% of the tendon displacement variance, and was significant at $\alpha \leq 0.01$, with the standard error of the regression of 1.52 mm.[141]

4.2.2.1 Assumptions

The major assumption upon which this model was used to calculate tendon travel was that the cumulative tendon excursion of the flexor tendons of the hand could be obtained by adding estimated tendon travel for each segments of the finger. It was also assumed that the axes of rotations of the joints of the fingers are fixed with respect to the proximal bone segments. In this model, the tendon is held securely against the curved articular surface of the proximal bone of the joint and the proximal articular surface can be described as a trochlea. Armstrong argued that the tendon is held against the trochlear structure by compression of palmar tissue and external load forces adjacent to the joints. Longitudinal cross-sectional photographs of the interdigit joints showed that the tendons closely follow the phalanges and did not show tendon bowstringing.[151]

4.2.2.2 Measures of wrist and finger joints

Assuming that wrist has an elliptic cross-sectional area, an empirical model (Equation 4) was used to calculate the wrist thickness as a function of wrist circumference, which we measured that of each subject prior to the keyboarding task.

$$\text{Elliptical Circumference} \approx 2\pi\sqrt{\frac{1}{2}(a^2 + b^2)} \tag{4}$$

In Equation 1, a and b are the long and short radii of the wrist cross-sectional area. Knowing the circumference and long radius (half of the distance between the wrist markers, as shown in Figure 10), wrist thickness for each subject was estimated. Anthropometric measurements of the finger joints were based on the data reported by Garrett.[152,153]

4.2.2.3 Tendon travel calculation

By integrating our anthropometric measurements and kinematics data into the model, we further modified this model to include individual characteristics such as wrist thickness and wrist and finger angles during keyboarding. The modified regression equations (Equations 5-12) were used to estimate tendon travel resulted by wrist and finger motions during keyboarding.

In these equations, "a" is the joint thickness (in mm) and "b" is the joint angle:

Tendon displacement (TD) for the PIP and MCP joints:

PIP joints:

1. Profundus tendon: $TD = 0.09356b + 0.004211ab$ (5)
2. Superficialis tendon: $TD = 0.07297b + 0.004211ab$ (6)

MCP joints:

1. Profundus tendon: $TD = 0.0872b + 0.004211ab$ (7)
2. Superficialis tendon: $TD = 0.1034b + 0.004211ab$ (8)

Tendon displacement (TD) for the wrist joint:

Flexion:

1. Profundus tendon: $TD = 0.1323b + 0.00404ab$ (9)
2. Superficialis tendon: $TD = 0.1323b + 0.00500ab$ (10)

Extension:

1. Profundus tendon: $TD = 0.0263b + 0.00404ab$ (11)
2. Superficialis tendon: $TD = 0.0263b + 0.00500ab$ (12)

Specifically, we calculated the amount of tendon displacement as a function of flexion angle and joint thickness for PIP and MCP joints of the index, middle, and ring finger, as well as wrist flexion and thickness, over four one-minute periods of keyboarding. The difference between positions at two consecutive time points was considered tendon travel at the second time point. Tendon travels were then averaged and the values of each segment (i.e., wrist, MCP, and PIP) for each finger were added and multiplied by 60 to estimate cumulative tendon travel (CTT) for the corresponding fingers in one hour.

4.2.2.4 Correlation analyses and linear regression models

Pearson Correlation tests were performed to find correlation between the average, peak, range of motion and cumulative tendon travel and changes in the ultrasound measures of the median nerve. In addition, linear regression models similar to those previously built in Chapter III were constructed to test whether the tendon travel could significantly contribute in predicting the acute change in the median nerve. The dependent variables of interest were the median nerve cross-sectional area at the pisiform level, swelling ratio, and flattening ratio and the independent variables of interest were the median nerve measures baseline values, subject characteristics, including age, gender, BMI, and keyboarding speed, as well as biomechanical variables such as wrist position (i.e., peak ulnar deviation and peak wrist flexion), keystroke reaction forces, and wrist average tendon travel.

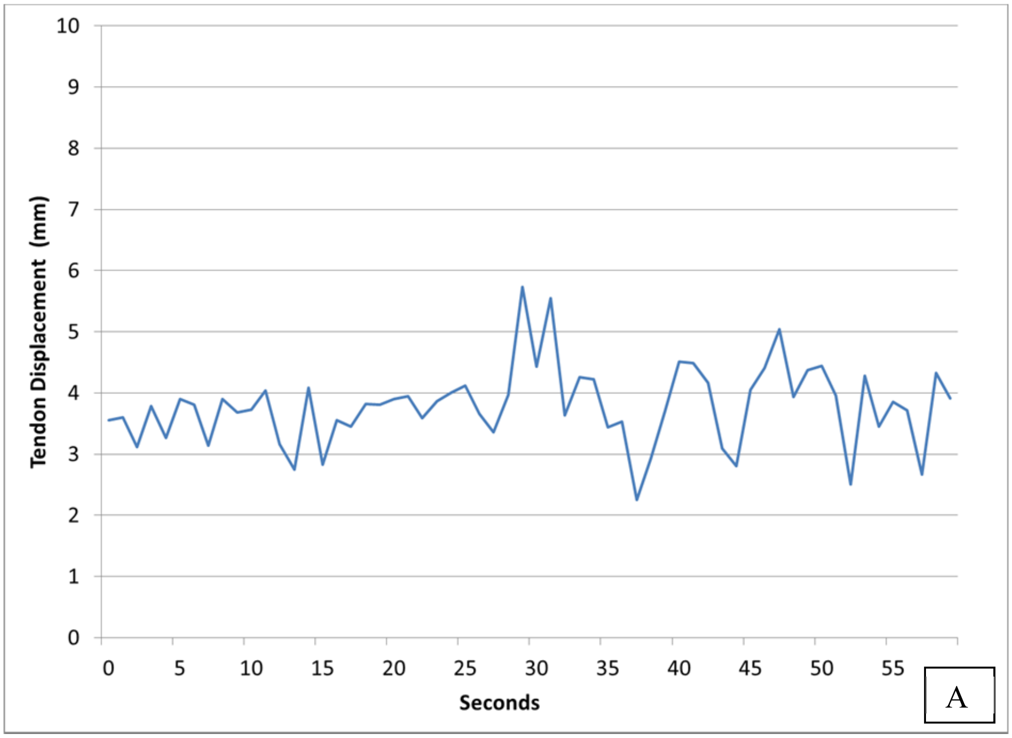
4.3 RESULTS

4.3.1 FDP and FDS Tendon Travel

The tendon travel of flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS) were found to be significantly correlated with a correlation coefficient of 0.99 across all fingers and wrist. As such, only tendon travel for FDP was used for the correlation analyses and linear regression models. Mean values and standard deviations for average, peak, range, and cumulative tendon travels for the FDP are shown in Table 15. Representative graphs demonstrating range of motion and tendon travel of the FDP tendon as a result of wrist flexion and flexion of index finger at PIP joint during a one-minute keyboarding task are shown in Figure 19 and Figure 20.

Table 15. Mean and standard deviation of peak, average, range, and cumulative tendon travel as a result of the index, middle, and ring fingers flexion and wrist flexion during keyboarding

Tendon Travel Mean ± SD		Peak (mm/sec)	Average (mm/sec)	Range (mm)	Cumulative (m/hour)
Index	PIP	4.23 ± 1.81	1.22 ± 0.47	4.21 ± 1.80	13.42
	MCP	5.02 ± 1.37	1.45 ± 0.41	4.99 ± 1.36	
Middle	PIP	4.52 ± 3.51	1.13 ± 0.46	4.50 ± 3.51	12.46
	MCP	4.65 ± 2.60	1.26 ± 0.40	4.62 ± 2.60	
Ring	PIP	7.61 ± 6.85	1.43 ± 0.62	7.58 ± 6.85	15.25
	MCP	9.36 ± 11.04	1.76 ± 1.48	9.33 ± 11.04	
Wrist Flexion		4.64 ± 7.99	1.12 ± 1.75	4.62 ± 8.00	



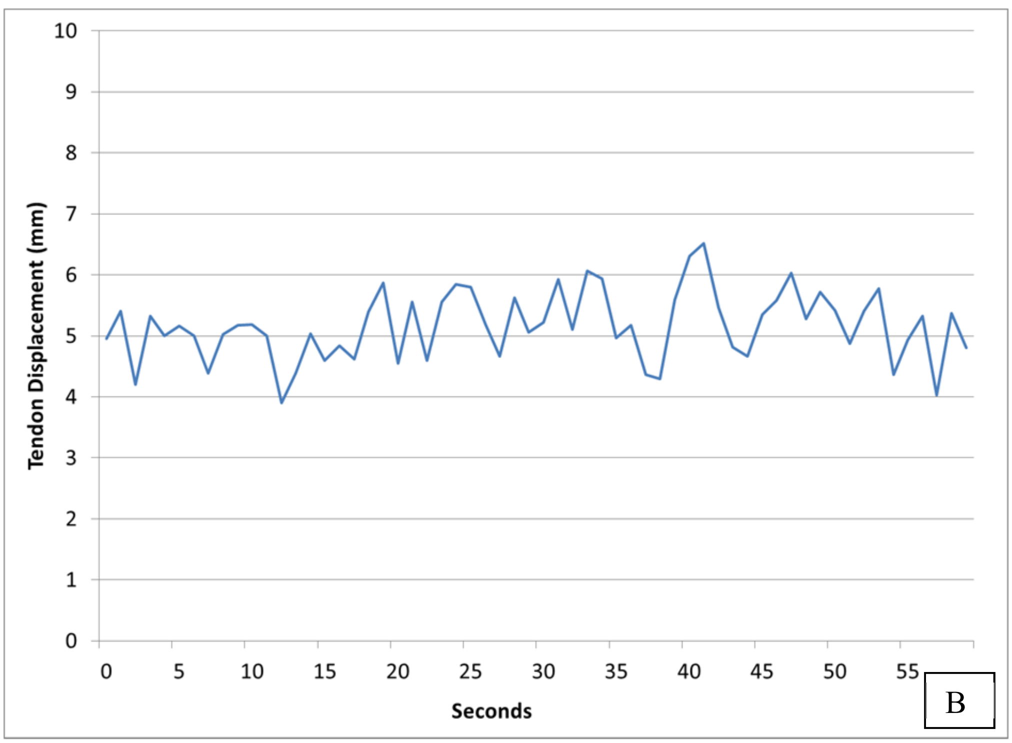


Figure 19. Exemplar graphs depicting the FDP tendon displacements as a result of wrist flexion, (A), and flexion of index finger at PIP joint, (B), during a one-minute keyboarding task

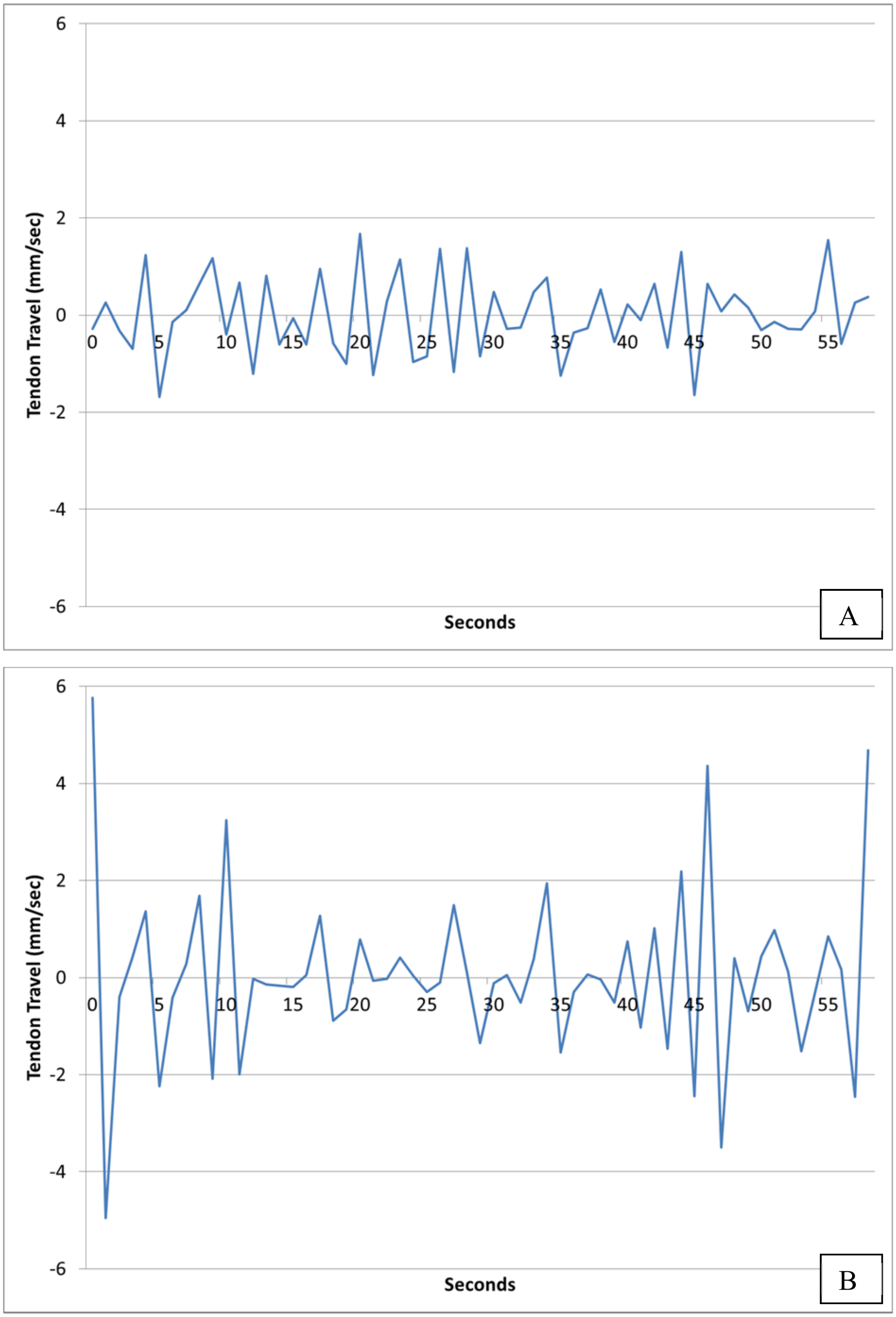


Figure 20. Exemplar graphs depicting the FDP tendon travels as a result of wrist flexion, (A), and flexion of index finger at PIP joint, (B), during a one-minute keyboarding task

4.3.2 Correlation Analyses

4.3.2.1 Tendon travel and subject characteristics

The average, peak and range of tendon travel for the wrist and three middle fingers as well as cumulative tendon travel (for the profundus tendons), or CTT, were tested against subject characteristics using Pearson Correlation analysis. The results were shown in Table 16 through Table 19.

Table 16. Coefficients of correlation between the range of tendon travels and the subject characteristics. P-values are shown in the parentheses.

	Gender	Age	BMI	Typing Speed
Index Finger	-0.079 (0.648)	0.186 (0.276)	0.210 (0.219)	0.040 (0.816)
Middle Finger	0.172 (0.316)	-0.096 (0.576)	-0.083 (0.631)	-0.078 (0.651)
Ring Finger	0.217 (0.205)	0.084 (0.626)	-0.182 (0.278)	0.065 (0.706)
Wrist	0.325 (0.053)	0.332* (0.048)	-0.160 (0.351)	0.379* (0.023)

Table 17. Coefficients of correlation between finger and wrist peak tendon travels and the subject characteristics. P-values are shown in the parentheses.

	Gender	Age	BMI	Typing Speed
Index Finger	-0.017 (0.922)	0.268 (0.115)	0.237 (0.164)	0.133 (0.439)
Middle Finger	0.204 (0.232)	-0.004 (0.982)	-0.111 (0.519)	-0.105 (0.543)
Ring Finger	0.345* (0.040)	0.042 (0.807)	-0.216 (0.206)	0.200 (0.241)
Wrist	0.328 (0.051)	0.525* (0.001)	-0.209 (0.222)	0.314 (0.063)

Table 18. Coefficients of correlation between finger and wrist average tendon travels and the subject characteristics. P-values are shown in the parentheses.

	Gender	Age	BMI	Typing Speed
Index Finger	-0.083 (0.632)	0.289 (0.088)	0.262 (0.122)	0.133 (0.440)
Middle Finger	0.184 (0.284)	0.119 (0.488)	-0.037 (0.828)	-0.026 (0.882)
Ring Finger	0.227 (0.183)	0.072 (0.675)	-0.165 (0.337)	0.017 (0.921)
Wrist	0.315 (0.062)	0.489* (0.002)	-0.158 (0.359)	0.331* (0.048)

Table 19. Coefficients of correlation between cumulative tendon travels and the subject characteristics. P-values are shown in the parentheses.

	Gender	Age	BMI	Typing Speed
Index Finger	0.284 (0.094)	0.476* (0.003)	-0.036 (0.835)	0.331* (0.049)
Middle Finger	0.381* (0.022)	0.416* (0.012)	-0.168 (0.327)	0.296 (0.079)
Ring Finger	0.258 (0.129)	0.395* (0.017)	-0.206 (0.227)	0.145 (0.397)

The results of our correlation analyses demonstrated that the values for wrist tendon travel (i.e., peak, average and range) are significantly correlated with subjects' age and typing speed. The tendon travel for the ring finger had also significant positive correlation with subjects' gender. In addition, the cumulative tendon travel showed significant positive correlation with subjects' age. The middle finger CTT and ring finger CTT were positively correlated with the subjects' gender and typing speed, respectively.

4.3.2.2 Tendon travel and wrist biomechanics

The average, peak and range of tendon travel for the wrist and three middle fingers and CTT (for the profundus tendons) were examined against subject characteristics using Pearson Correlation analysis. The results were shown in Table 20 through Table 23.

Table 20. Coefficients of correlation between the range of tendon travels and the wrist biomechanics. P-values are shown in the parentheses.

	Peak Wrist Flexion	Peak Wrist Ulnar Deviation	Average Force
Index Finger	0.047 (0.748)	-0.326 (0.052)	-0.167 (0.331)
Middle Finger	-0.170 (0.321)	-0.087 (0.614)	-0.127 (0.462)
Ring Finger	-0.196 (0.253)	-0.082 (0.633)	0.067 (0.698)
Wrist	-0.146 (0.395)	-0.344* (0.042)	0.022 (0.897)

Table 21. Coefficients of correlation between the peak tendon travels and the wrist biomechanics. P-values are shown in the parentheses.

	Peak Wrist Flexion	Peak Wrist Ulnar Deviation	Average Force
Index Finger	0.051 (0.769)	-0.323 (0.054)	-0.186 (0.279)
Middle Finger	-0.171 (0.319)	-0.067 (0.696)	-0.132 (0.444)
Ring Finger	-0.148 (0.388)	-0.213 (0.212)	0.106 (0.539)
Wrist	-0.030 (0.862)	-0.435* (0.008)	0.127 (0.460)

Table 22. Coefficients of correlation between the average tendon travels and the wrist biomechanics. P-values are shown in the parentheses.

	Peak Wrist Flexion	Peak Wrist Ulnar Deviation	Average Force
Index Finger	0.054 (0.753)	-0.365* (0.029)	-0.133 (0.440)
Middle Finger	-0.212 (0.214)	-0.223 (0.191)	-0.095 (0.581)
Ring Finger	-0.081 (0.639)	-0.142 (0.409)	0.082 (0.636)
Wrist	-0.023 (0.894)	-0.400* (0.016)	0.130 (0.449)

Table 23. Coefficients of correlation between the cumulative tendon travels and the wrist biomechanics. P-values are shown in the parentheses.

	Peak Wrist Flexion	Peak Wrist Ulnar Deviation	Average Force
Index Finger	-0.034 (0.845)	-0.440* (0.007)	0.084 (0.628)
Middle Finger	-0.138 (0.421)	-0.363* (0.030)	0.093 (0.591)
Ring Finger	-0.063 (0.717)	-0.345* (0.040)	0.156 (0.362)

The results of these correlation analyses indicated that the values for wrist tendon travel (i.e., peak, average and range) were significantly correlated with peak wrist ulnar deviation. The average tendon travel for the ring finger had also significant negative correlation with peak wrist ulnar deviation. In addition, all three fingers' cumulative tendon travel showed significant negative correlation with peak wrist ulnar deviation.

4.3.2.3 Tendon travel and the median nerve measurements

Pearson Correlation was also used to investigate correlation between the median nerve ultrasound measures and cumulative tendon travels. The correlation coefficients and corresponding p-values are shown in Table 24. This analysis found significant positive correlation only between CTT and the flattening ratio at the baseline. The middle finger CTT was also significantly correlated to the FR at the 30-minute time point.

Table 24. Coefficients of correlation between the cumulative tendon travels and the median nerve measures. P-values are shown in the parentheses.

		Index	**Middle**	**Ring**
CSA	Baseline	0.204 (0.234)	0.126 (0.463)	0.096 (0.578)
	30-min	0.171 (0.319)	0.103 (0.549)	0.064 (0.709)
	60-min	0.106 (0.540)	0.072 (0.676)	0.107 (0.533)
Swelling Ratio	Baseline	-0.072 (0.675)	-0.064 (0.709)	-0.050 (0.772)
	30-min	-0.160 (0.352)	-0.195 (0.255)	-0.196 (0.251)
	60-min	-0.297 (0.079)	-0.244 (0.152)	-0.213 (0.213)
Flattening Ratio	Baseline	0.546* (0.001)	0.487* (0.002)	0.330* (0.049)
	30-min	0.377 (0.023)	0.340* (0.043)	0.198 (0.247)
	60-min	0.231 (0.181)	0.207 (0.233)	0.039 (0.825)

4.3.3 Linear Regression Models

Based on the results of the correlation analyses, the wrist average tendon travel was selected as an independent variable to build linear regression models similar to those previously introduced in Chapter II (Figure 24). The R-squared and p-values for the independent variable are summarized in Table 25. The complete test results are presented in Appendix B.

A. CSA-30 = -1.474 + (0.998 * CSA_Baseline) + (0.279 * Gender) + (0.0138 * Age) + (0.0644 * BMI) + (0.00886 * Typing Speed) - (0.0182 * Peak wrist flexion) + (0.0197 * Peak wrist ulnar deviation) - (0.129 * Average Force) - (0.109 * TT_wrist_average)

CSA-60 = 3.246 + (0.902 * CSA_Baseline) + (0.238 * Gender) + (0.00467 * Age) - (0.0344 * BMI) - (0.0132 * Typing Speed) - (0.0180 * Peak wrist flexion) + (0.000150 * Peak wrist ulnar deviation) + (0.0736 * Average Force) - (0.0283 * TT_wrist_average)

B. CSA-60 = 3.246 + (0.902 * CSA_Baseline) + (0.238 * Gender) + (0.00467 * Age) - (0.0344 * BMI) - (0.0132 * Typing Speed) - (0.0180 * Peak wrist flexion) + (0.000150 * Peak wrist ulnar deviation) + (0.0736 * Average Force) - (0.0283 * TT_wrist_average)

SR-60 = 0.624 + (0.491 * SR_Baseline) + (0.0548 * Gender) - (0.00248 * Age) + (0.000598 * BMI) + (0.00119 * Typing Speed) - (0.00346 * Peak wrist flexion) + (0.00229 * Peak wrist ulnar deviation) - (0.00629 * Average Force) + (0.00985 * TT_wrist_average)

C. FR-30 = 1.095 + (0.606 * FR_Baseline) + (0.0632 * Gender) - (0.0134 * Age) + (0.00587 * BMI) - (0.00299 * Typing Speed) + (0.0197 * Peak wrist flexion) - (0.0123 * Peak wrist ulnar deviation) + (0.00883 * Average Force) + (0.0582 * TT_wrist_average)

FR-60 = 0.465 + (0.508 * FR_Baseline) + (0.0624 * Gender) - (0.00809 * Age) - (0.00973 * BMI) + (0.0117 * Typing Speed) + (0.0229 * Peak wrist flexion) + (0.00764 * Peak wrist ulnar deviation) - (0.0766 * Average Force) + (0.111 * TT_wrist_average)

Equations 13. Multiple linear regression models that incorporated baseline values, subjects characteristics, biomechanical variables and wrist average tendon travel to predict values of the median nerve CSA (A), swelling ratio (B), and flattening ratio (C) following the keyboarding task

Table 25. P-value for the subject characteristic in the linear regression models presented above and R-squared values for each model. Asterisks indicate statistical significance.

	Cross-sectional Area		Swelling Ratio		Flattening Ratio	
	30	**60**	**30**	**60**	**30**	**60**
R^2	0.850	0.725	0.580	0.481	0.623	0.573
Constant	0.419	0.133	0.952	0.045	0.201	0.619
Baseline	<0.001	<0.001	<0.001	0.015	<0.001	<0.001
Gender	0.495	0.616	0.677	0.304	0.742	0.775
Age	0.633	0.889	0.881	0.546	0.355	0.612
BMI	0.099	0.439	0.605	0.901	0.744	0.646
Typing Speed	0.598	0.500	0.489	0.609	0.730	0.261
Wrist Flexion	0.336	0.412	0.655	0.169	0.041	0.040
Ulnar Deviation	0.294	0.994	0.461	0.369	0.185	0.463
Average Force	0.411	0.685	0.255	0.766	0.913	0.394
Average Wrist TT	0.302	0.816	0.253	0.466	0.256	0.056

All three models demonstrated a relatively high R-squared value (Table 11) and power of performed tests with alpha = 0.050 was 1.00. Once again, the baseline values appeared to account for the ability to predict the median nerve measures at the other time points. No subject characteristic or biomechanical factor, including the average wrist tendon travel, was found to be a significant contributor in models for the CSA and swelling ratio. However, peak wrist flexion was able to significantly participate in predicting the flattening ratio values in the corresponding regression model.

4.4 DISCUSSION

4.4.1 Significance

Previously, it was demonstrated that one-hour continuous keyboarding caused acute changes in the ultrasonographic characteristics of median nerve. We investigated some of the relevant biomechanical variables of keyboarding, including wrist and finger movements and positions during keyboarding, and were able to explore significant correlations between those variables and median nerve measures.

Tendon travel has been shown to be a measure of biomechanical stress in the carpal canal. It has been studied rather extensively because of its possible role in the development of MSD-UE such as carpal tunnel syndrome. Nelson et al. reported that, on average, the tendon travel for 1 hour of continuous typing ranged from 30 to 59 m.[144] Repetitive sliding of tendons within their sheaths will increase the friction that is a major trigger for the disorders of the tendons, their sheaths or adjacent nerves.[128] Quantifying the amount of movement of the tendons provides means to investigate the risk of median nerve injuries as a result of repetitive manual tasks.

In this study, we used an established methodology to calculate tendon travel as a result of flexion of the wrist and index, middle, and ring fingers during keyboarding. Using keyboarding kinematic data and anthropometric measurements, we were able to modify the regression models that have been previously tested by empirical data. This helped us include individual differences in our calculation to obtain results that reflect the effects of geometrical and biomechanical variables among population. The results of this study were consistent with those that have previously reported in biomechanical literature.

In particular, our estimation of FDP and FDS tendon travel was found to be in the range that has been reported in literature.[141,144,145] Specifically, the cumulative tendon travel for one hour of continuous typing was estimated to range from 12.5 m to 15.3 m. The results also closely matched predicted tendon displacement values that have been reported for so-called “small” female and “large” male.[144,145] The tendon travel calculations were followed by correlation analyses, which revealed several significant correlations between the tendon travel and subject characteristics, wrist biomechanical factors, as well as acute changes in the median nerve measures. Therefore, we were able to achieve both major goals of this study, i.e., calculating tendon travel during a keyboarding event, and finding correlation between this biomechanical variable and acute changes in median nerve. Furthermore, the multiple linear regression models (Appendix B) that combined several individual and biomechanical variables were constructed to predict the changes in median nerve measures during keyboarding. In fact, one of these models demonstrated significant contribution from the wrist average tendon travel in predicting changes in the median nerve flattening ratio during a manual task such as keyboarding. Significant correlations between the tendon travel and multiple subject characteristics, some of the biomechanical factors, and acute changes in median nerve variables that were observed in this study suggest that tendon travel may play a major role in the median nerve pathophysiology. It is notable that tendon travel was significantly correlated with the variables, such as wrist ulnar deviation, that have been previously recognized as harmful wrist postures with causal relationship to the upper extremity musculoskeletal disorders.

4.4.2 Limitations

Obviously, we are aware of several limitations in our study. The regression equations from Armstrong and Chaffin, although not outdated, are relatively old. Despite many more recent biomechanical models for movement of hand and fingers, these equations were found to be the best fit for our experimental data, as they integrate not only the most relevant motions of the fingers and wrist during keyboarding, but allow to incorporate individual differences such wrist circumference and joint thicknesses. These regression models, however, are sensitive only to motion in the flexion/extension plane; other three-dimensional effects, such as abduction/adduction of the index finger at the metacarpal joint, are not evaluated here. What has been calculated in this study as tendon travel only incorporates movements of the tendons as a result of flexion of three fingers (i.e., index, middle, and ring) at only two joints (i.e., MCP and PIP). Obviously, this is not a complete representation of flexor tendon excursions during keyboarding and how tendon travel can contribute to changes in the median nerve over that period of time. The methodology however was proved to be appropriate for such a study since the overall results were in agreement with those in the current literature. In addition, force analysis is not included in this model and viscoelastic and inertial effects of biological systems are not taken into account.

Although collecting anthropometric data helped us improve the modified Armstrong model, the lack of certain measurements, including PIP, DIP and MCP joint thickness, limited our approach to completely tailor the model to individual subjects. Adding such a simple measurements that can be taken relatively fast and easily in future work will help improve the current model even further. Furthermore, including data from thumb and little finger would add to the accuracy of the model. Since it has been suggested that keyboarding is not necessarily a symmetric task, collecting kinematic data from non-dominant hand and wrist will provide an opportunity to compare both sides in order to gain better understanding of keyboarding biomechanics.

4.5 CONCLUSIONS

The purpose of this study was twofold: first, we aimed to utilize a biomechanical model of the hand and fingers to calculate tendon travel during a keyboarding assignment. Second, values of tendon excursion obtained through the biomechanical model were used to find a correlation between this biomechanical variable and acute changes in the ultrasonographic measures of the median nerve that have been observed in our previous study. Our results demonstrated that average wrist tendon travel, perhaps as an indicator of biomechanical stress in the carpal tunnel and a potential contributing factor in development of median nerve injury, can be predicted via our suggested biomechanical model. Furthermore, we found significant correlations between this variable and acute changes in median nerve measures. This finding further indicated the importance of evaluating biomechanical parameters in studying conditions that are thought to be caused as a result of repetitive strain injury such as carpal tunnel syndrome. Comprehensive and long-term research studies are required in order to elucidate the still unclear relationship between the biomechanical attributes and CTS pathogenesis.

5.0 CONCLUSIONS

5.1 SIGNIFICANCE

Carpal tunnel syndrome (CTS) is the most commonly reported nerve entrapment syndrome,[6] affecting over 8-million Americans.[154] CTS is also the most common and costly repetitive strain injury of the upper extremity,[155] which results in the highest number of days lost per case among all work-related disorders.[156] According to the National Center for Health Statistics, almost half of the CTS cases resulted in 31 days or more of work loss.[157] The non-medical costs of a CTS case (from compensation settlements and disability) are reported to be approximately $10,000 for each hand.[158] Szabo estimated that this sum is increased by the medical cost and indirect costs that raises it to $20,000–$100,000/hand.[158] According to the U.S. Department of Labor, up to 36% of all CTS patients require lifelong medical treatment.[154]

In a very comprehensive review article, Fagarasanu and Kumar outlined relevant information about CTS risk factors present in data entry task and their implications.[159] They concluded that, although many different studies have examined possible associations of keyboarding-related posture and activity on carpal tunnel syndrome occurrence, evaluating the complex relationships between the different causal factors implicated in keyboarding and work-related CTS remains a complicated task.

5.2 SUMMARY OF FINDINGS

In our study, we aimed to elucidate the implicated relationships between carpal tunnel syndrome and some of the causal factors associated with keyboarding by combining different medical and biomechanical approaches and investigating the effects of a prolonged keyboarding task on the median nerve characteristics. Using ultrasonography, we demonstrated that a continuous keyboarding assignment caused acute changes in the median nerve measures, which have been previously linked to both symptoms and pathology of carpal tunnel syndrome. This suggests that keyboarding has a direct impact on the median nerve. In addition, our results showed that the changes in the median nerve decreased following a resting period, supporting a causal relationship between keyboarding and changes of the median nerve measurements.

Furthermore, the observed changes in the median nerve were found to be significantly correlated with certain individual characteristics, as well as biomechanical variables related to the keyboarding. These correlations were rather sporadic; nevertheless, they highlighted the importance of personal factors, such as age, BMI, typing speed, and anthropometric parameters, in pathophysiology of the median nerve injury, consistent with that reported in biomechanical and medical literature.[160-164] The findings also underlined the effects of keyboarding biomechanics on the median nerve response and provide insight into understanding how combination of several physical and mechanical factors can contribute to development of median nerve injuries.

While the results of our study further indicated that the median nerve pathophysiology is multifactorial, it appears that some variables play a greater role in the median nerve injury mechanism. In particular, individual characteristics such as age and BMI seemed to be more relevant than gender. Also, typing speed, as an indicator of task frequency, showed a more significant effect on the median nerve acute changes when compared to other biomechanical potential risk factors, including wrist posture and/or keystroke forces. This finding was consistent with that was previously reported in the biomechanical literature.[2,6] Mechanisms such as repetition appear to cause histological changes, which could be inflammation, in the median nerve, which can lead to enlargement of the nerve in the tunnel, hence larger cross sectional area. Other possible mechanisms that are suggested to be responsible for tissue damage include ischemia caused by compression-related narrowed blood vessels[12] and viscoelastic creep responses related to cumulative strain on the tendons[13] due to tendon travel. Naturally, a higher typing speed would accelerate such a process by increasing the amount of strain in a given time unit. Personal factors, such as larger BMI (which may cause a decrease in tunnel diameter) and age, would enhance these pathophysiologic mechanisms. Further investigations are required to either confirm or rule out any of these speculations.

5.3 LIMITATIONS

While the results of our study indicate that the median nerve exhibits an immediate response to the keyboarding task, we are aware that CTS is not an "acute" disorder. In fact, many studies described carpal tunnel pathophysiology as a chronic and cumulative process. In particular, Fagarasanu listed "time on task" and "percentage of time typing" among the most common risk factors in the review article.[159] As such, one may question the relevance or significance of a relatively short keyboarding assignment, when compared to, for instance, long hours of data entry in a daily basis. After all, it is possible that the acute changes in the median nerve are physiological responses to repetition and will fade away shortly after the task is completed.

The main purpose of this study was to establish a baseline understanding of keyboarding biomechanics in healthy subjects. By testing people with no signs of CTS we are selecting a population that may be at less risk to injury. We believe this is needed to remove clinical variability from the study. However, by not including CTS (or other median neuropathy) patients, we missed the opportunity to make comparison between our findings and potentially different results in the individuals with median nerve disorders. Furthermore, including only one group of subjects (i.e., healthy participants) was considered a flaw in our study design, as we did not have any control group. Ideally, subjects in the control group would do nothing manually during a period of time equivalent to the periods where the other participants would keyboard. This would allow investigating any possible changes in the median nerve measures in the absence of a manual activity such as keyboarding, and the data could be used to perform more comprehensive statistical analyses.

As discussed before, research has shown that there is great variety in preferred postures/styles among different keyboard users that appear to be related to the physical characteristics of the workstation.[55,59,63,90] In our study, we did not attempt to recreate each subject's work set up as we believe attempting to recreate the workstation would add variability to the experiment. Evaluating the potential effects of physical setup of the workstation on the median nerve measures must be included in future studies.

The usage of computer mouse during the keyboarding task was purposefully eliminated. Working with the mouse is a major component of computer use, and frequency, duration and style of using a mouse may be important factors that can affect wrist posture and result in median nerve injury over time. Fogleman and Brogmus reported that, due to the adoption of the graphical user interfaces, pointing devices (e.g., computer mouse, trackballs) are present in every office environment.[111] The use of the mouse has been reported to account for almost 60% of total time in most applications[112-114] with a maximum level of usage of 65–70% in drawing applications.[115] The lateral position of the mouse, due to the original workstation design that took into consideration only the keyboard, causing the abduction of the arm[116,117] with the wrist ulnar deviated,[118] extended, high muscular tension and fatigue. These, plus the prolonged awkward postures have been reported as risk factors for CTS.[119,120] Our study focused on the keyboarding aspect only and the role of mouse or other pointing devices will be the subject of future studies.

Based on the current design of our study, we collected biomechanical data only from the dominant side, while we examined both sides through the clinical ultrasound examinations. It has been suggested that keyboarding is not a symmetrical task.[88] Dvorak suggested that a conventional QWERTY keyboard causes overloading of the "weaker" left hand in a right-handed person.[121] Many studies have concluded similar or additional outcomes since then and reported differences between left and right forearms and wrists during keyboarding.[61,62,122,123] As such, reporting biomechanical data for only the dominant side is another limitation in this study that needs to be addressed in future studies.

Furthermore, insufficient kinetics data (i.e., keystroke forces collected at 8 Hz) limited our study to thoroughly investigate the effects of reaction forces applied to fingers during the keyboarding task on the median nerve measures. While the range of collected data was in agreement with the current literature, we suspect that our study did not necessarily record all the forces applied to the fingers, and peak forces especially could have been missed out. Finally, the lack of anthropometric measurements of the MCP and PIP joints for each participant prevented our regression models from being individually-tailored for each subject. By adding such a simple measurement to future studies, one would speculate that a more subject-specific calculation could improve the biomechanical model and further elucidate the relationship between the tendon travel and acute changes in the median nerve characteristics.

5.4 FUTURE DIRECTIONS

The median nerve exhibited acute changes in response to a keyboarding task. This is further evidence of a potential causal relationship between computer keyboarding and median nerve injuries such as carpal tunnel syndrome. Further studies, however, are required to elaborate on any possible pathophysiologic mechanism over time. Specifically, longitudinal studies must be designed to follow up median nerve changes in participants who continue keyboarding in a frequent manner.

Inclusion of subjects with known median nerve pathology (e.g., diagnosed carpal tunnel syndrome patients) in future studies may help investigators differentiate the median nerve response to a repetitive task, like keyboarding, in a physiologic as opposed to a pathologic condition, since it has been shown that changes in the median nerve resulting from keyboarding may be less likely to occur in subjects with symptoms of carpal tunnel syndrome.[34]

Using the same methodology as outlined in this study, the effects of computer mouse or other pointing devices can be investigated to find the correlation between biomechanical aspects of using mouse, such as prolonged awkward postures, and median nerve measures. Furthermore, assuming our current study provided a baseline to evaluate the effects of keyboarding on median nerve, a logical next step will be to compare the acute changes in the median nerve and the corresponding wrist biomechanical variables between the baseline testing and those that obtained after changing the workstation setup (i.e., changing the keyboard position or using ergonomic keyboard). This information will provide an opportunity to develop interventions specific to these biomechanical risk factors in subsequent controlled trials.

Finally, the biomechanical data can be used to develop a true mathematical model to predict the effects of generated forces and motions at the wrist and fingers during typing on the median nerve characteristics. One way to develop this model will be using OpenSim,[165] a freely available open-source software package, developed and maintained on Simtk.org, for modeling and simulating musculoskeletal systems. Its plug-in capabilities allow users to develop customize analyses, controllers, and muscle models, among other things, and share plug-ins without the need to alter or compile source code. OpenSim also allows users to develop and analyze new and existing models and simulations. Since its introduction in 2007, many people have begun to utilize the software in a wide variety of applications, for example, biomechanical research, orthopedics, and neuroscience research, to name a few. Using such methodology will provide a more comprehensive approach to understand multifactorial nature of median nerve pathology and helps the investigators intervene with the harmful habits and postures to prevent acute and chronic injuries to the median nerve as a result of keyboarding or any other repetitive manual tasks.

APPENDIX A

REGRESSION MODELS WITHOUT TENDON TRAVEL

Multiple Linear Regression Tuesday, November 15, 2011, 1:46:56 PM

Data source: CSA, SR, and FR in Keyboarding Data

CSA_30 minute = -2.020 + (1.017 * CSA_Baseline) + (0.569 * Gender) + (0.00177 * age) + (0.0588 * BMI) + (0.00921 * Typing Speed)

N = 36

R = 0.911 Rsqr = 0.831 Adj Rsqr = 0.802

Standard Error of Estimate = 0.938

	Coefficient	Std. Error	t	P	VIF
Constant	-2.020	1.382	-1.462	0.154	
CSA_Baseline	1.017	0.0977	10.414	<0.001	1.249
Gender	0.569	0.362	1.571	0.127	1.340
age	0.00177	0.0247	0.0719	0.943	1.070
BMI	0.0588	0.0369	1.592	0.122	1.167
Typing Speed	0.00921	0.0162	0.568	0.574	1.258

Analysis of Variance:

	DF	SS	MS	F	P
Regression	5	129.506	25.901	29.409	<0.001
Residual	30	26.422	0.881		
Total	35	155.928	4.455		

Column	SSIncr	SSMarg
CSA_Baseline	123.992	95.522
Gender	2.889	2.174
age	0.0664	0.00456
BMI	2.275	2.232
Typing Speed	0.284	0.284

The dependent variable CSA_30 minute can be predicted from a linear combination of the independent variables:

	P
CSA_Baseline	<0.001
Gender	0.127
age	0.943
BMI	0.122
Typing Speed	0.574

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict CSA_30 minute (P < 0.05): CSA_Baseline

Normality Test: Passed (P = 0.856)

Constant Variance Test: Passed (P = 0.336)

Power of performed test with alpha = 0.050: 1.000

Multiple Linear Regression Tuesday, November 15, 2011, 1:49:30 PM

Data source: CSA, SR, and FR in Keyboarding Data

CSA_60 minute = 2.988 + (0.901 * CSA_Baseline) + (0.348 * Gender) + (0.00116 * age) - (0.0367 * BMI) - (0.0129 * Typing Speed)

N = 36

R = 0.846 Rsqr = 0.716 Adj Rsqr = 0.668

Standard Error of Estimate = 1.044

	Coefficient	**Std. Error**	**t**	**P**	**VIF**
Constant	2.988	1.537	1.945	0.061	
CSA_Baseline	0.901	0.109	8.293	<0.001	1.249
Gender	0.348	0.403	0.864	0.395	1.340
age	0.00116	0.0275	0.0422	0.967	1.070
BMI	-0.0367	0.0411	-0.894	0.378	1.167
Typing Speed	-0.0129	0.0180	-0.716	0.480	1.258

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	5	82.316	16.463	15.110	<0.001
Residual	30	32.687	1.090		
Total	35	115.002	3.286		

Column	**SSIncr**	**SSMarg**
CSA_Baseline	80.183	74.932
Gender	0.648	0.813
age	0.0179	0.00194
BMI	0.909	0.872
Typing Speed	0.558	0.558

The dependent variable CSA_60 minute can be predicted from a linear combination of the independent variables:

	P
CSA_Baseline	<0.001
Gender	0.395
age	0.967
BMI	0.378
Typing Speed	0.480

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict CSA_60 minute (P < 0.05): CSA_Baseline

Normality Test: Passed (P = 0.221)

Constant Variance Test: Passed (P = 0.964)

Power of performed test with alpha = 0.050: 1.000

Multiple Linear Regression Tuesday, November 15, 2011, 2:14:19 PM

Data source: CSA, SR, and FR in Keyboarding Data

SR_30 minute = 0.0922 + (0.817 * SR_Baseline) + (0.0408 * Gender) - (0.000157 * age) + (0.00264 * BMI) + (0.00135 * Typing Speed)

N = 36

R = 0.714 Rsqr = 0.509 Adj Rsqr = 0.428

Standard Error of Estimate = 0.126

	Coefficient	**Std. Error**	**t**	**P**	**VIF**
Constant	0.0922	0.267	0.346	0.732	
SR_Baseline	0.817	0.180	4.551	<0.001	1.436
Gender	0.0408	0.0481	0.849	0.403	1.315
age	-0.000157	0.00377	-0.0417	0.967	1.385
BMI	0.00264	0.00476	0.553	0.584	1.079
Typing Speed	0.00135	0.00227	0.593	0.558	1.372

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	5	0.493	0.0987	6.231	<0.001
Residual	30	0.475	0.0158		
Total	35	0.968	0.0277		

Column	**SSIncr**	**SSMarg**
SR_Baseline	0.462	0.328
Gender	0.0192	0.0114
age	0.000568	0.0000275
BMI	0.00628	0.00485
Typing Speed	0.00557	0.00557

The dependent variable SR_30 minute can be predicted from a linear combination of the independent variables:

	P
SR_Baseline	<0.001
Gender	0.403
age	0.967
BMI	0.584
Typing Speed	0.558

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict SR_30 minute (P < 0.05): SR_Baseline

Normality Test: Passed (P = 0.641)

Constant Variance Test: Passed (P = 0.134)

Power of performed test with alpha = 0.050: 0.999

Multiple Linear Regression Tuesday, November 15, 2011, 2:20:45 PM

Data source: CSA, SR, and FR in Keyboarding Data

SR_60 minute = 0.653 + (0.507 * SR_Baseline) + (0.0715 * Gender) - (0.00514 * age) - (0.000753 * BMI) + (0.00103 * Typing Speed)

N = 36

R = 0.644 Rsqr = 0.414 Adj Rsqr = 0.317

Standard Error of Estimate = 0.123

	Coefficient	Std. Error	t	P	VIF
Constant	0.653	0.262	2.495	0.018	
SR_Baseline	0.507	0.176	2.880	0.007	1.436
Gender	0.0715	0.0471	1.517	0.140	1.315
age	-0.00514	0.00369	-1.393	0.174	1.385
BMI	-0.000753	0.00467	-0.161	0.873	1.079
Typing Speed	0.00103	0.00223	0.462	0.648	1.372

Analysis of Variance:

	DF	SS	MS	F	P
Regression	5	0.322	0.0645	4.243	0.005
Residual	30	0.456	0.0152		
Total	35	0.779	0.0222		

Column	SSIncr	SSMarg
SR_Baseline	0.242	0.126
Gender	0.0499	0.0350
age	0.0268	0.0295
BMI	0.000172	0.000396
Typing Speed	0.00324	0.00324

The dependent variable SR_60 minute can be predicted from a linear combination of the independent variables:

	P
SR_Baseline	0.007
Gender	0.140
age	0.174
BMI	0.873
Typing Speed	0.648

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict SR_60 minute (P < 0.05): SR_Baseline

Normality Test: Passed (P = 0.694)

Constant Variance Test: Passed (P = 0.727)

Power of performed test with alpha = 0.050: 0.992

Multiple Linear Regression Tuesday, November 15, 2011, 2:32:44 PM

Data source: CSA, SR, and FR in Keyboarding Data

FR_30 minute = 1.218 + (0.630 * FR_Baseline) - (0.126 * Gender) - (0.00372 * age) + (0.00964 * BMI) - (0.00367 * Typing Speed)

N = 36

R = 0.722 Rsqr = 0.521 Adj Rsqr = 0.442

Standard Error of Estimate = 0.488

	Coefficient	Std. Error	t	P	VIF
Constant	1.218	0.673	1.811	0.080	
FR_Baseline	0.630	0.116	5.436	<0.001	1.147
Gender	-0.126	0.182	-0.694	0.493	1.245
age	-0.00372	0.0129	-0.288	0.776	1.087
BMI	0.00964	0.0184	0.524	0.604	1.071
Typing Speed	-0.00367	0.00862	-0.425	0.674	1.314

Analysis of Variance:

	DF	SS	MS	F	P
Regression	5	7.794	1.559	6.539	<0.001
Residual	30	7.151	0.238		
Total	35	14.945	0.427		

Column	SSIncr	SSMarg
FR_Baseline	7.384	7.043
Gender	0.289	0.115
age	0.0201	0.0197
BMI	0.0575	0.0653
Typing Speed	0.0431	0.0431

The dependent variable FR_30 minute can be predicted from a linear combination of the independent variables:

	P
FR_Baseline	<0.001
Gender	0.493
age	0.776
BMI	0.604
Typing Speed	0.674

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict FR_30 minute (P < 0.05): FR_Baseline

Normality Test: Passed (P = 0.751)

Constant Variance Test: Passed (P = 0.294)

Power of performed test with alpha = 0.050: 0.999

Multiple Linear Regression Tuesday, November 15, 2011, 2:33:33 PM

Data source: CSA, SR, and FR in Keyboarding Data

FR_60 minute = 1.449 + (0.551 * FR_Baseline) - (0.0942 * Gender) - (0.0110 * age) - (0.00600 * BMI) + (0.00689 * Typing Speed)

N = 35 Missing Observations = 1

R = 0.655 Rsqr = 0.429 Adj Rsqr = 0.330

Standard Error of Estimate = 0.551

	Coefficient	Std. Error	t	P	VIF
Constant	1.449	0.769	1.883	0.070	
FR_Baseline	0.551	0.131	4.213	<0.001	1.147
Gender	-0.0942	0.215	-0.438	0.664	1.329
age	-0.0110	0.0149	-0.740	0.465	1.086
BMI	-0.00600	0.0220	-0.273	0.787	1.119
Typing Speed	0.00689	0.0101	0.681	0.501	1.396

Analysis of Variance:

	DF	SS	MS	F	P
Regression	5	6.616	1.323	4.354	0.004
Residual	29	8.812	0.304		
Total	34	15.428	0.454		

Column	SSIncr	SSMarg
FR_Baseline	6.323	5.395
Gender	0.0145	0.0584
age	0.129	0.166
BMI	0.00836	0.0227
Typing Speed	0.141	0.141

The dependent variable FR_60 minute can be predicted from a linear combination of the independent variables:

	P
FR_Baseline	<0.001
Gender	0.664
age	0.465
BMI	0.787
Typing Speed	0.501

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict FR_60 minute (P < 0.05): FR_Baseline

Normality Test: Passed (P = 0.252)

Constant Variance Test: Passed (P = 0.854)

Power of performed test with alpha = 0.050: 0.993

Multiple Linear Regression Tuesday, November 15, 2011, 2:39:29 PM

Data source: CSA, SR, FR in Keyboarding Data

CSA_30 minute = 0.608 + (1.061 * CSA_Baseline) - (0.0170 * Peak wrist flexion) + (0.0126 * Peak wrist ulnar deviation) - (0.152 * Average Force (N))

N = 36

R = 0.899 Rsqr = 0.809 Adj Rsqr = 0.784

Standard Error of Estimate = 0.980

	Coefficient	Std. Error	t	P	VIF
Constant	0.608	1.138	0.535	0.597	
CSA_Baseline	1.061	0.0932	11.393	<0.001	1.041
Peak wrist flexion	-0.0170	0.0178	-0.955	0.347	1.050
Peak wrist ulnar deviation	0.0126	0.0168	0.750	0.459	1.100
Average Force (N)	-0.152	0.156	-0.973	0.338	1.112

Analysis of Variance:

	DF	SS	MS	F	P
Regression	4	126.142	31.535	32.820	<0.001
Residual	31	29.786	0.961		
Total	35	155.928	4.455		

Column	SSIncr	SSMarg
CSA_Baseline	123.992	124.712
Peak wrist flexion	1.015	0.877
Peak wrist ulnar deviation	0.226	0.540
Average Force (N)	0.909	0.909

The dependent variable CSA_30 minute can be predicted from a linear combination of the independent variables:

	P
CSA_Baseline	<0.001
Peak wrist flexion	0.347
Peak wrist ulnar deviation	0.459
Average Force (N)	0.338

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict CSA_30 minute (P < 0.05): CSA_Baseline

Normality Test: Passed (P = 0.593)

Constant Variance Test: Passed (P = 0.916)

Power of performed test with alpha = 0.050: 1.000

Multiple Linear Regression Tuesday, November 15, 2011, 2:40:31 PM

Data source: CSA, SR, FR in Keyboarding Data

CSA_60 minute = 2.400 + (0.852 * CSA_Baseline) - (0.0202 * Peak wrist flexion) + (0.00332 * Peak wrist ulnar deviation) + (0.0656 * Average Force (N))

N = 36

R = 0.842 Rsqr = 0.709 Adj Rsqr = 0.672

Standard Error of Estimate = 1.038

	Coefficient	Std. Error	t	P	VIF
Constant	2.400	1.205	1.992	0.055	
CSA_Baseline	0.852	0.0987	8.640	<0.001	1.041
Peak wrist flexion	-0.0202	0.0188	-1.075	0.291	1.050
Peak wrist ulnar deviation	0.00332	0.0178	0.187	0.853	1.100
Average Force (N)	0.0656	0.165	0.397	0.694	1.112

Analysis of Variance:

	DF	SS	MS	F	P
Regression	4	81.594	20.398	18.928	<0.001
Residual	31	33.408	1.078		
Total	35	115.002	3.286		

Column	SSIncr	SSMarg
CSA_Baseline	80.183	80.457
Peak wrist flexion	1.132	1.245
Peak wrist ulnar deviation	0.109	0.0376
Average Force (N)	0.170	0.170

The dependent variable CSA_60 minute can be predicted from a linear combination of the independent variables:

	P
CSA_Baseline	<0.001
Peak wrist flexion	0.291
Peak wrist ulnar deviation	0.853
Average Force (N)	0.694

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict CSA_60 minute (P < 0.05): CSA_Baseline

Normality Test: Passed (P = 0.558)

Constant Variance Test: Passed (P = 0.732)

Power of performed test with alpha = 0.050: 1.000

Multiple Linear Regression Tuesday, November 15, 2011, 2:42:15 PM

Data source: CSA, SR, FR in Keyboarding Data

SR_30 minute = 0.201 + (0.798 * SR_Baseline) - (0.00107 * Peak wrist flexion) + (0.00163 * Peak wrist ulnar deviation) + (0.0190 * Average Force (N))

N = 36

R = 0.716 Rsqr = 0.512 Adj Rsqr = 0.449

Standard Error of Estimate = 0.123

	Coefficient	Std. Error	t	P	VIF
Constant	0.201	0.183	1.101	0.279	
SR_Baseline	0.798	0.159	5.033	<0.001	1.163
Peak wrist flexion	-0.00107	0.00220	-0.487	0.630	1.016
Peak wrist ulnar deviation	0.00163	0.00225	0.723	0.475	1.249
Average Force (N)	0.0190	0.0203	0.940	0.354	1.182

Analysis of Variance:

	DF	SS	MS	F	P
Regression	4	0.496	0.124	8.144	<0.001
Residual	31	0.472	0.0152		
Total	35	0.968	0.0277		

Column	SSIncr	SSMarg
SR_Baseline	0.462	0.386
Peak wrist flexion	0.00169	0.00361
Peak wrist ulnar deviation	0.0194	0.00797
Average Force (N)	0.0135	0.0135

The dependent variable SR_30 minute can be predicted from a linear combination of the independent variables:

	P
SR_Baseline	<0.001
Peak wrist flexion	0.630
Peak wrist ulnar deviation	0.475
Average Force (N)	0.354

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict SR_30 minute (P < 0.05): SR_Baseline

Normality Test: Passed (P = 0.818)

Constant Variance Test: Passed (P = 0.134)

Power of performed test with alpha = 0.050: 0.999

Multiple Linear Regression Tuesday, November 15, 2011, 2:42:59 PM

Data source: CSA, SR, FR in Keyboarding Data

SR_60 minute = 0.675 + (0.532 * SR_Baseline) - (0.00487 * Peak wrist flexion) + (0.00264 * Peak wrist ulnar deviation) - (0.00874 * Average Force (N))

N = 36

R = 0.660 Rsqr = 0.436 Adj Rsqr = 0.363

Standard Error of Estimate = 0.119

	Coefficient	Std. Error	t	P	VIF
Constant	0.675	0.176	3.836	<0.001	
SR_Baseline	0.532	0.153	3.478	0.002	1.163
Peak wrist flexion	-0.00487	0.00212	-2.292	0.029	1.016
Peak wrist ulnar deviation	0.00264	0.00217	1.217	0.233	1.249
Average Force (N)	-0.00874	0.0195	-0.448	0.658	1.182

Analysis of Variance:

	DF	SS	MS	F	P
Regression	4	0.339	0.0848	5.985	0.001
Residual	31	0.439	0.0142		
Total	35	0.779	0.0222		

Column	SSIncr	SSMarg
SR_Baseline	0.242	0.171
Peak wrist flexion	0.0759	0.0745
Peak wrist ulnar deviation	0.0181	0.0210
Average Force (N)	0.00284	0.00284

The dependent variable SR_60 minute can be predicted from a linear combination of the independent variables:

	P
SR_Baseline	0.002
Peak wrist flexion	0.029
Peak wrist ulnar deviation	0.233
Average Force (N)	0.658

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict SR_60 minute (P < 0.05): SR_Baseline , Peak wrist flexion

Normality Test: Passed (P = 0.390)

Constant Variance Test: Passed (P = 0.359)

Power of performed test with alpha = 0.050: 0.995

Multiple Linear Regression Tuesday, November 15, 2011, 2:45:40 PM

Data source: CSA, SR, FR in Keyboarding Data

FR_30 minute = 0.849 + (0.572 * FR_Baseline) + (0.0174 * Peak wrist flexion) - (0.00885 * Peak wrist ulnar deviation) + (0.0188 * Average Force (N))

N = 36

R = 0.758 Rsqr = 0.574 Adj Rsqr = 0.519

Standard Error of Estimate = 0.453

	Coefficient	Std. Error	t	P	VIF
Constant	0.849	0.415	2.046	0.049	
FR_Baseline	0.572	0.105	5.429	<0.001	1.101
Peak wrist flexion	0.0174	0.00811	2.146	0.040	1.024
Peak wrist ulnar deviation	-0.00885	0.00775	-1.142	0.262	1.099
Average Force (N)	0.0188	0.0749	0.251	0.804	1.200

Analysis of Variance:

	DF	SS	MS	F	P
Regression	4	8.579	2.145	10.443	<0.001
Residual	31	6.366	0.205		
Total	35	14.945	0.427		

Column	SSIncr	SSMarg
FR_Baseline	7.384	6.052
Peak wrist flexion	0.925	0.945
Peak wrist ulnar deviation	0.257	0.268
Average Force (N)	0.0129	0.0129

The dependent variable FR_30 minute can be predicted from a linear combination of the independent variables:

	P
FR_Baseline	<0.001
Peak wrist flexion	0.040
Peak wrist ulnar deviation	0.262
Average Force (N)	0.804

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict FR_30 minute (P < 0.05): FR_Baseline , Peak wrist flexion

Normality Test: Passed (P = 0.591)

Constant Variance Test: Passed (P = 0.851)

Power of performed test with alpha = 0.050: 1.000

Multiple Linear Regression Tuesday, November 29, 2011, 4:01:15 PM

Data source: FINAL ANALYSES in Keyboarding Data

FR-60 = 0.946 + (0.570 * FR_Baseline) + (0.0149 * Peak wrist flexion) + (0.00678 * Peak wrist ulnar deviation) - (0.0939 * Average Force)

N = 35 Missing Observations = 1

R = 0.688 Rsqr = 0.473 Adj Rsqr = 0.403

Standard Error of Estimate = 0.521

	Coefficient	**Std. Error**	**t**	**P**	**VIF**
Constant	0.946	0.494	1.916	0.065	
FR_Baseline	0.570	0.121	4.703	<0.001	1.103
Peak wrist flexion	0.0149	0.00954	1.563	0.128	1.021
Peak wrist ulnar deviation	0.00678	0.00920	0.737	0.467	1.085
Average Force	-0.0939	0.0861	-1.091	0.284	1.183

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	4	7.300	1.825	6.736	<0.001
Residual	30	8.128	0.271		
Total	34	15.428	0.454		

Column	**SSIncr**	**SSMarg**
FR_Baseline	6.323	5.992
Peak wrist flexion	0.599	0.662
Peak wrist ulnar deviation	0.0558	0.147
Average Force	0.322	0.322

The dependent variable FR-60 can be predicted from a linear combination of the independent variables:

	P
FR_Baseline	<0.001
Peak wrist flexion	0.128
Peak wrist ulnar deviation	0.467
Average Force	0.284

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict FR-60 (P < 0.05): FR_Baseline

Normality Test: Passed (P = 0.189)

Constant Variance Test: Passed (P = 0.354)

Power of performed test with alpha = 0.050: 0.998

Multiple Linear Regression Tuesday, November 15, 2011, 2:51:52 PM

Data source: CSA, SR, FR in Keyboarding Data

CSA_30 minute = -2.184 + (1.020 * CSA_Baseline) + (0.410 * Gender) + (0.0195 * age) + (0.0655 * BMI) + (0.00924 * Typing Speed) - (0.0155 * Peak wrist flexion) + (0.0220 * Peak wrist ulnar deviation) - (0.142 * Average Force (N))

N = 36

R = 0.919 Rsqr = 0.844 Adj Rsqr = 0.798

Standard Error of Estimate = 0.949

	Coefficient	Std. Error	t	P	VIF
Constant	-2.184	1.668	-1.309	0.201	
CSA_Baseline	1.020	0.0994	10.259	<0.001	1.264
Gender	0.410	0.384	1.069	0.294	1.471
age	0.0195	0.0281	0.694	0.494	1.352
BMI	0.0655	0.0377	1.739	0.093	1.186
Typing Speed	0.00924	0.0166	0.555	0.583	1.295
Peak wrist flexion	-0.0155	0.0184	-0.845	0.406	1.200
Peak wrist ulnar deviation	0.0220	0.0183	1.201	0.240	1.396
Average Force (N)	-0.142	0.154	-0.926	0.363	1.151

Analysis of Variance:

	DF	SS	MS	F	P
Regression	8	131.599	16.450	18.256	<0.001
Residual	27	24.329	0.901		
Total	35	155.928	4.455		

Column	SSIncr	SSMarg
CSA_Baseline	123.992	94.831
Gender	2.889	1.030
age	0.0664	0.434
BMI	2.275	2.726
Typing Speed	0.284	0.278
Peak wrist flexion	0.488	0.643
Peak wrist ulnar deviation	0.833	1.299
Average Force (N)	0.772	0.772

The dependent variable CSA_30 minute can be predicted from a linear combination of the independent variables:

	P
CSA_Baseline	<0.001
Gender	0.294
age	0.494
BMI	0.093
Typing Speed	0.583
Peak wrist flexion	0.406
Peak wrist ulnar deviation	0.240
Average Force (N)	0.363

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).

The following appear to account for the ability to predict CSA_30 minute ($P < 0.05$): CSA_Baseline

Normality Test: Passed ($P = 0.365$)

Constant Variance Test: Passed ($P = 0.727$)

Power of performed test with alpha = 0.050: 1.000

Multiple Linear Regression Tuesday, November 15, 2011, 2:53:02 PM

Data source: CSA, SR, FR in Keyboarding Data

CSA_60 minute = 3.061 + (0.907 * CSA_Baseline) + (0.273 * Gender) + (0.00614 * age) - (0.0341 * BMI) - (0.0131 * Typing Speed) - (0.0173 * Peak wrist flexion) + (0.000741 * Peak wrist ulnar deviation) + (0.0700 * Average Force (N))

N = 36

R = 0.851 Rsqr = 0.724 Adj Rsqr = 0.642

Standard Error of Estimate = 1.084

	Coefficient	**Std. Error**	**t**	**P**	**VIF**
Constant	3.061	1.905	1.607	0.120	
CSA_Baseline	0.907	0.113	7.993	<0.001	1.264
Gender	0.273	0.438	0.622	0.539	1.471
age	0.00614	0.0320	0.192	0.849	1.352
BMI	-0.0341	0.0430	-0.793	0.435	1.186
Typing Speed	-0.0131	0.0190	-0.691	0.495	1.295
Peak wrist flexion	-0.0173	0.0210	-0.824	0.417	1.200
Peak wrist ulnar deviation	0.000741	0.0209	0.0355	0.972	1.396
Average Force (N)	0.0700	0.175	0.399	0.693	1.151

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	8	83.283	10.410	8.861	<0.001
Residual	27	31.719	1.175		
Total	35	115.002	3.286		

Column	**SSIncr**	**SSMarg**
CSA_Baseline	80.183	75.047
Gender	0.648	0.455
age	0.0179	0.0432
BMI	0.909	0.739
Typing Speed	0.558	0.561
Peak wrist flexion	0.748	0.797
Peak wrist ulnar deviation	0.0328	0.00148
Average Force (N)	0.187	0.187

The dependent variable CSA_60 minute can be predicted from a linear combination of the independent variables:

	P
CSA_Baseline	<0.001
Gender	0.539
age	0.849
BMI	0.435
Typing Speed	0.495
Peak wrist flexion	0.417
Peak wrist ulnar deviation	0.972
Average Force (N)	0.693

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).

The following appear to account for the ability to predict CSA_60 minute ($P < 0.05$): CSA_Baseline

Normality Test: Passed ($P = 0.167$)

Constant Variance Test: Passed ($P = 0.844$)

Power of performed test with alpha = 0.050: 1.000

Multiple Linear Regression Tuesday, November 15, 2011, 2:54:27 PM

Data source: CSA, SR, FR in Keyboarding Data

SR_30 minute = -0.0940 + (0.819 * SR_Baseline) + (0.0373 * Gender) + (0.00139 * age) + (0.00297 * BMI) + (0.00185 * Typing Speed) - (0.000671 * Peak wrist flexion) + (0.00227 * Peak wrist ulnar deviation) + (0.0222 * Average Force (N))

N = 36

R = 0.747 Rsqr = 0.558 Adj Rsqr = 0.427

Standard Error of Estimate = 0.126

	Coefficient	**Std. Error**	**t**	**P**	**VIF**
Constant	-0.0940	0.292	-0.322	0.750	
SR_Baseline	0.819	0.190	4.319	<0.001	1.601
Gender	0.0373	0.0511	0.731	0.471	1.483
age	0.00139	0.00403	0.344	0.734	1.590
BMI	0.00297	0.00481	0.618	0.542	1.099
Typing Speed	0.00185	0.00232	0.796	0.433	1.434
Peak wrist flexion	-0.000671	0.00244	-0.275	0.786	1.202
Peak wrist ulnar deviation	0.00227	0.00251	0.907	0.372	1.491
Average Force (N)	0.0222	0.0210	1.056	0.300	1.222

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	8	0.541	0.0676	4.267	0.002
Residual	27	0.428	0.0158		
Total	35	0.968	0.0277		

Column	**SSIncr**	**SSMarg**
SR_Baseline	0.462	0.295
Gender	0.0192	0.00846
age	0.000568	0.00187
BMI	0.00628	0.00606
Typing Speed	0.00557	0.0100
Peak wrist flexion	0.0000266	0.00120
Peak wrist ulnar deviation	0.0297	0.0130
Average Force (N)	0.0177	0.0177

The dependent variable SR_30 minute can be predicted from a linear combination of the independent variables:

	P
SR_Baseline	<0.001
Gender	0.471
age	0.734
BMI	0.542
Typing Speed	0.433
Peak wrist flexion	0.786
Peak wrist ulnar deviation	0.372
Average Force (N)	0.300

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).

The following appear to account for the ability to predict SR_30 minute ($P < 0.05$): SR_Baseline

Normality Test: Passed ($P = 0.457$)

Constant Variance Test: Passed ($P = 0.307$)

Power of performed test with alpha = 0.050: 1.000

Multiple Linear Regression Tuesday, November 15, 2011, 2:55:22 PM

Data source: CSA, SR, FR in Keyboarding Data

SR_60 minute = 0.672 + (0.498 * SR_Baseline) + (0.0452 * Gender) - (0.00297 * age) + (0.000306 * BMI) + (0.00105 * Typing Speed) - (0.00373 * Peak wrist flexion) + (0.00204 * Peak wrist ulnar deviation) - (0.00492 * Average Force (N))

N = 36

R = 0.686 Rsqr = 0.471 Adj Rsqr = 0.314

Standard Error of Estimate = 0.124

	Coefficient	Std. Error	t	P	VIF
Constant	0.672	0.286	2.344	0.027	
SR_Baseline	0.498	0.186	2.676	0.013	1.601
Gender	0.0452	0.0501	0.901	0.376	1.483
age	-0.00297	0.00396	-0.749	0.461	1.590
BMI	0.000306	0.00472	0.0648	0.949	1.099
Typing Speed	0.00105	0.00228	0.462	0.648	1.434
Peak wrist flexion	-0.00373	0.00240	-1.557	0.131	1.202
Peak wrist ulnar deviation	0.00204	0.00246	0.829	0.414	1.491
Average Force (N)	-0.00492	0.0206	-0.238	0.813	1.222

Analysis of Variance:

	DF	SS	MS	F	P
Regression	8	0.366	0.0458	2.999	0.015
Residual	27	0.412	0.0153		
Total	35	0.779	0.0222		

Column	SSIncr	SSMarg
SR_Baseline	0.242	0.109
Gender	0.0499	0.0124
age	0.0268	0.00856
BMI	0.000172	0.0000642
Typing Speed	0.00324	0.00325
Peak wrist flexion	0.0333	0.0370
Peak wrist ulnar deviation	0.00967	0.0105
Average Force (N)	0.000868	0.000868

The dependent variable SR_60 minute can be predicted from a linear combination of the independent variables:

	P
SR_Baseline	0.013
Gender	0.376
age	0.461
BMI	0.949
Typing Speed	0.648
Peak wrist flexion	0.131
Peak wrist ulnar deviation	0.414
Average Force (N)	0.813

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).

The following appear to account for the ability to predict SR_60 minute ($P < 0.05$): SR_Baseline

Normality Test: Passed ($P = 0.359$)

Constant Variance Test: Passed ($P = 0.276$)

Power of performed test with alpha = 0.050: 0.998

Multiple Linear Regression Tuesday, November 15, 2011, 2:57:02 PM

Data source: CSA, SR, FR in Keyboarding Data

FR_30 minute = 1.423 + (0.623 * FR_Baseline) + (0.00305 * Gender) - (0.0168 * age) + (0.00401 * BMI) - (0.00408 * Typing Speed) + (0.0180 * Peak wrist flexion) - (0.0137 * Peak wrist ulnar deviation) + (0.0120 * Average Force (N))

N = 36

R = 0.777 Rsqr = 0.603 Adj Rsqr = 0.486

Standard Error of Estimate = 0.469

	Coefficient	Std. Error	t	P	VIF
Constant	1.423	0.790	1.800	0.083	
FR_Baseline	0.623	0.120	5.178	<0.001	1.344
Gender	0.00305	0.184	0.0166	0.987	1.385
age	-0.0168	0.0140	-1.207	0.238	1.372
BMI	0.00401	0.0178	0.225	0.824	1.091
Typing Speed	-0.00408	0.00857	-0.476	0.638	1.410
Peak wrist flexion	0.0180	0.00912	1.969	0.059	1.210
Peak wrist ulnar deviation	-0.0137	0.00903	-1.520	0.140	1.398
Average Force (N)	0.0120	0.0801	0.150	0.882	1.282

Analysis of Variance:

	DF	SS	MS	F	P
Regression	8	9.016	1.127	5.133	<0.001
Residual	27	5.929	0.220		
Total	35	14.945	0.427		

Column	SSIncr	SSMarg
FR_Baseline	7.384	5.887
Gender	0.289	0.0000606
age	0.0201	0.320
BMI	0.0575	0.0111
Typing Speed	0.0431	0.0497
Peak wrist flexion	0.699	0.852
Peak wrist ulnar deviation	0.519	0.507
Average Force (N)	0.00495	0.00495

The dependent variable FR_30 minute can be predicted from a linear combination of the independent variables:

	P
FR_Baseline	<0.001
Gender	0.987
age	0.238
BMI	0.824
Typing Speed	0.638
Peak wrist flexion	0.059
Peak wrist ulnar deviation	0.140
Average Force (N)	0.882

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).

The following appear to account for the ability to predict FR_30 minute ($P < 0.05$): FR_Baseline

Normality Test: Passed ($P = 0.325$)

Constant Variance Test: Passed ($P = 0.271$)

Power of performed test with alpha = 0.050: 1.000

Multiple Linear Regression Tuesday, November 15, 2011, 2:57:46 PM

Data source: CSA, SR, FR in Keyboarding Data

FR_60 minute = 1.097 + (0.543 * FR_Baseline) - (0.0484 * Gender) - (0.0146 * age) - (0.0128 * BMI) + (0.00933 * Typing Speed) + (0.0193 * Peak wrist flexion) + (0.00480 * Peak wrist ulnar deviation) - (0.0711 * Average Force (N))

N = 35 Missing Observations = 1

R = 0.710 Rsqr = 0.504 Adj Rsqr = 0.351

Standard Error of Estimate = 0.543

	Coefficient	**Std. Error**	**t**	**P**	**VIF**
Constant	1.097	0.919	1.194	0.243	
FR_Baseline	0.543	0.141	3.862	<0.001	1.367
Gender	-0.0484	0.220	-0.220	0.828	1.442
age	-0.0146	0.0163	-0.898	0.377	1.344
BMI	-0.0128	0.0221	-0.578	0.568	1.168
Typing Speed	0.00933	0.0107	0.874	0.390	1.602
Peak wrist flexion	0.0193	0.0110	1.761	0.090	1.244
Peak wrist ulnar deviation	0.00480	0.0107	0.447	0.659	1.360
Average Force (N)	-0.0711	0.0932	-0.763	0.452	1.275

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	8	7.772	0.971	3.299	0.010
Residual	26	7.656	0.294		
Total	34	15.428	0.454		

Column	**SSIncr**	**SSMarg**
FR_Baseline	6.323	4.392
Gender	0.0145	0.0142
age	0.129	0.237
BMI	0.00836	0.0983
Typing Speed	0.141	0.225
Peak wrist flexion	0.963	0.913
Peak wrist ulnar deviation	0.0214	0.0587
Average Force (N)	0.171	0.171

The dependent variable FR_60 minute can be predicted from a linear combination of the independent variables:

	P
FR_Baseline	<0.001
Gender	0.828
age	0.377
BMI	0.568
Typing Speed	0.390
Peak wrist flexion	0.090
Peak wrist ulnar deviation	0.659
Average Force (N)	0.452

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).

The following appear to account for the ability to predict FR_60 minute ($P < 0.05$): FR_Baseline

Normality Test: Passed ($P = 0.137$)

Constant Variance Test: Passed ($P = 0.462$)

Power of performed test with alpha = 0.050: 0.999

APPENDIX B

REGRESSION MODELS WITH TENDON TRAVEL

Multiple Linear Regression Tuesday, November 29, 2011, 4:28:26 PM

Data source: FINAL ANALYSES in Keyboarding Data

CSA-30 = -1.474 + (0.998 * CSA_Baseline) + (0.279 * Gender) + (0.0138 * Age) + (0.0644 * BMI) + (0.00886 * Typing Speed) - (0.0182 * Peak wrist flexion) + (0.0197 * Peak wrist ulnar deviation) - (0.129 * Average Force) - (0.109 * TT_wrist_average)

N = 36

R = 0.922 Rsqr = 0.850 Adj Rsqr = 0.799

Standard Error of Estimate = 0.947

	Coefficient	**Std. Error**	**t**	**P**	**VIF**
Constant	-1.474	1.796	-0.820	0.419	
CSA_Baseline	0.998	0.101	9.858	<0.001	1.317
Gender	0.279	0.403	0.692	0.495	1.628
Age	0.0138	0.0285	0.484	0.633	1.402
BMI	0.0644	0.0376	1.713	0.099	1.187
Typing Speed	0.00886	0.0166	0.533	0.598	1.296
Peak wrist flexion	-0.0182	0.0185	-0.981	0.336	1.222
Peak wrist ulnar deviation	0.0197	0.0184	1.071	0.294	1.416
Average Force	-0.129	0.154	-0.835	0.411	1.159
TT_wrist_average	-0.109	0.103	-1.053	0.302	1.272

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	9	132.595	14.733	16.416	<0.001
Residual	26	23.334	0.897		
Total	35	155.928	4.455		

Column	**SSIncr**	**SSMarg**
CSA_Baseline	123.992	87.217
Gender	2.889	0.430
Age	0.0664	0.210
BMI	2.275	2.634
Typing Speed	0.284	0.255
Peak wrist flexion	0.488	0.864
Peak wrist ulnar deviation	0.833	1.030
Average Force	0.772	0.626
TT_wrist_average	0.995	0.995

The dependent variable CSA-30 can be predicted from a linear combination of the independent variables:

	P
CSA_Baseline	<0.001
Gender	0.495
Age	0.633
BMI	0.099
Typing Speed	0.598
Peak wrist flexion	0.336
Peak wrist ulnar deviation	0.294
Average Force	0.411
TT_wrist_average	0.302

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).
The following appear to account for the ability to predict CSA-30 ($P < 0.05$): CSA_Baseline

Normality Test: Passed ($P = 0.315$)

Constant Variance Test: Passed ($P = 0.559$)

Power of performed test with alpha = 0.050: 1.000

Multiple Linear Regression Tuesday, November 29, 2011, 4:33:51 PM

Data source: FINAL ANALYSES in Keyboarding Data

CSA-60 = 3.246 + (0.902 * CSA_Baseline) + (0.238 * Gender) + (0.00467 * Age) - (0.0344 * BMI) - (0.0132 * Typing Speed) - (0.0180 * Peak wrist flexion) + (0.000150 * Peak wrist ulnar deviation) + (0.0736 * Average Force) - (0.0283 * TT_wrist_average)

N = 36

R = 0.851 Rsqr = 0.725 Adj Rsqr = 0.630

Standard Error of Estimate = 1.103

	Coefficient	Std. Error	t	P	VIF
Constant	3.246	2.092	1.551	0.133	
CSA_Baseline	0.902	0.118	7.644	<0.001	1.317
Gender	0.238	0.469	0.508	0.616	1.628
Age	0.00467	0.0332	0.140	0.889	1.402
BMI	-0.0344	0.0438	-0.785	0.439	1.187
Typing Speed	-0.0132	0.0194	-0.684	0.500	1.296
Peak wrist flexion	-0.0180	0.0216	-0.833	0.412	1.222
Peak wrist ulnar deviation	0.000150	0.0214	0.00701	0.994	1.416
Average Force	0.0736	0.179	0.410	0.685	1.159
TT_wrist_average	-0.0283	0.120	-0.235	0.816	1.272

Analysis of Variance:

	DF	SS	MS	F	P
Regression	9	83.351	9.261	7.607	<0.001
Residual	26	31.652	1.217		
Total	35	115.002	3.286		

Column	SSIncr	SSMarg
CSA_Baseline	80.183	71.133
Gender	0.648	0.314
Age	0.0179	0.0240
BMI	0.909	0.751
Typing Speed	0.558	0.570
Peak wrist flexion	0.748	0.846
Peak wrist ulnar deviation	0.0328	0.0000598
Average Force	0.187	0.205
TT_wrist_average	0.0675	0.0675

The dependent variable CSA-60 can be predicted from a linear combination of the independent variables:

	P
CSA_Baseline	<0.001
Gender	0.616
Age	0.889
BMI	0.439
Typing Speed	0.500
Peak wrist flexion	0.412
Peak wrist ulnar deviation	0.994
Average Force	0.685
TT_wrist_average	0.816

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).
The following appear to account for the ability to predict CSA-60 ($P < 0.05$): CSA_Baseline

Normality Test: Passed ($P = 0.139$)

Constant Variance Test: Passed ($P = 0.746$)

Power of performed test with alpha = 0.050: 1.000

Multiple Linear Regression Tuesday, November 29, 2011, 4:36:26 PM

Data source: FINAL ANALYSES in Keyboarding Data

SR-30 = -0.0182 + (0.830 * SR_Baseline) + (0.0221 * Gender) + (0.000614 * Age) + (0.00251 * BMI) + (0.00162 * Typing Speed) - (0.00111 * Peak wrist flexion) + (0.00188 * Peak wrist ulnar deviation) + (0.0243 * Average Force) - (0.0156 * TT_wrist_average)

N = 36

R = 0.762 Rsqr = 0.580 Adj Rsqr = 0.435

Standard Error of Estimate = 0.125

	Coefficient	Std. Error	t	P	VIF
Constant	-0.0182	0.297	-0.0613	0.952	
SR_Baseline	0.830	0.189	4.402	<0.001	1.605
Gender	0.0221	0.0524	0.421	0.677	1.581
Age	0.000614	0.00406	0.151	0.881	1.633
BMI	0.00251	0.00479	0.524	0.605	1.106
Typing Speed	0.00162	0.00231	0.702	0.489	1.444
Peak wrist flexion	-0.00111	0.00245	-0.452	0.655	1.231
Peak wrist ulnar deviation	0.00188	0.00251	0.749	0.461	1.518
Average Force	0.0243	0.0209	1.163	0.255	1.232
TT_wrist_average	-0.0156	0.0134	-1.170	0.253	1.224

Analysis of Variance:

	DF	SS	MS	F	P
Regression	9	0.562	0.0625	3.997	0.003
Residual	26	0.406	0.0156		
Total	35	0.968	0.0277		

Column	SSIncr	SSMarg
SR_Baseline	0.462	0.303
Gender	0.0192	0.00277
Age	0.000568	0.000357
BMI	0.00628	0.00429
Typing Speed	0.00557	0.00770
Peak wrist flexion	0.0000266	0.00319
Peak wrist ulnar deviation	0.0297	0.00876
Average Force	0.0177	0.0211
TT_wrist_average	0.0214	0.0214

The dependent variable SR-30 can be predicted from a linear combination of the independent variables:

	P
SR_Baseline	<0.001
Gender	0.677
Age	0.881
BMI	0.605
Typing Speed	0.489
Peak wrist flexion	0.655
Peak wrist ulnar deviation	0.461
Average Force	0.255
TT_wrist_average	0.253

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).
The following appear to account for the ability to predict SR-30 ($P < 0.05$): SR_Baseline

Normality Test: Passed ($P = 0.290$)

Constant Variance Test: Passed ($P = 0.167$)

Power of performed test with alpha = 0.050: 1.000

Multiple Linear Regression Tuesday, November 29, 2011, 4:38:20 PM

Data source: FINAL ANALYSES in Keyboarding Data

SR-60 = 0.624 + (0.491 * SR_Baseline) + (0.0548 * Gender) - (0.00248 * Age) + (0.000598 * BMI) + (0.00119 * Typing Speed) - (0.00346 * Peak wrist flexion) + (0.00229 * Peak wrist ulnar deviation) - (0.00629 * Average Force) + (0.00985 * TT_wrist_average)

N = 36

R = 0.694 Rsqr = 0.481 Adj Rsqr = 0.302

Standard Error of Estimate = 0.125

	Coefficient	Std. Error	t	P	VIF
Constant	0.624	0.296	2.107	0.045	
SR_Baseline	0.491	0.188	2.612	0.015	1.605
Gender	0.0548	0.0522	1.049	0.304	1.581
Age	-0.00248	0.00405	-0.612	0.546	1.633
BMI	0.000598	0.00477	0.125	0.901	1.106
Typing Speed	0.00119	0.00231	0.517	0.609	1.444
Peak wrist flexion	-0.00346	0.00245	-1.413	0.169	1.231
Peak wrist ulnar deviation	0.00229	0.00250	0.913	0.369	1.518
Average Force	-0.00629	0.0209	-0.301	0.766	1.232
TT_wrist_average	0.00985	0.0133	0.739	0.466	1.224

Analysis of Variance:

	DF	SS	MS	F	P
Regression	9	0.375	0.0417	2.682	0.024
Residual	26	0.404	0.0155		
Total	35	0.779	0.0222		

Column	SSIncr	SSMarg
SR_Baseline	0.242	0.106
Gender	0.0499	0.0171
Age	0.0268	0.00582
BMI	0.000172	0.000243
Typing Speed	0.00324	0.00415
Peak wrist flexion	0.0333	0.0310
Peak wrist ulnar deviation	0.00967	0.0130
Average Force	0.000868	0.00141
TT_wrist_average	0.00849	0.00849

The dependent variable SR-60 can be predicted from a linear combination of the independent variables:

	P
SR_Baseline	0.015
Gender	0.304
Age	0.546
BMI	0.901
Typing Speed	0.609
Peak wrist flexion	0.169
Peak wrist ulnar deviation	0.369
Average Force	0.766
TT_wrist_average	0.466

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).
The following appear to account for the ability to predict SR-60 ($P < 0.05$): SR_Baseline

Normality Test: Passed ($P = 0.261$)

Constant Variance Test: Passed ($P = 0.386$)

Power of performed test with alpha = 0.050: 0.998

Multiple Linear Regression Tuesday, November 29, 2011, 4:40:28 PM

Data source: FINAL ANALYSES in Keyboarding Data

FR-30 = 1.095 + (0.606 * FR_Baseline) + (0.0632 * Gender) - (0.0134 * Age) + (0.00587 * BMI) - (0.00299 * Typing Speed) + (0.0197 * Peak wrist flexion) - (0.0123 * Peak wrist ulnar deviation) + (0.00883 * Average Force) + (0.0582 * TT_wrist_average)

N = 36

R = 0.789 Rsqr = 0.623 Adj Rsqr = 0.492

Standard Error of Estimate = 0.466

	Coefficient	Std. Error	t	P	VIF
Constant	1.095	0.834	1.312	0.201	
FR_Baseline	0.606	0.121	5.021	<0.001	1.366
Gender	0.0632	0.190	0.333	0.742	1.497
Age	-0.0134	0.0142	-0.941	0.355	1.436
BMI	0.00587	0.0178	0.330	0.744	1.100
Typing Speed	-0.00299	0.00857	-0.348	0.730	1.428
Peak wrist flexion	0.0197	0.00918	2.145	0.041	1.243
Peak wrist ulnar deviation	-0.0123	0.00906	-1.361	0.185	1.423
Average Force	0.00883	0.0796	0.111	0.913	1.284
TT_wrist_average	0.0582	0.0501	1.162	0.256	1.241

Analysis of Variance:

	DF	SS	MS	F	P
Regression	9	9.309	1.034	4.772	<0.001
Residual	26	5.636	0.217		
Total	35	14.945	0.427		

Column	SSIncr	SSMarg
FR_Baseline	7.384	5.465
Gender	0.289	0.0240
Age	0.0201	0.192
BMI	0.0575	0.0236
Typing Speed	0.0431	0.0263
Peak wrist flexion	0.699	0.998
Peak wrist ulnar deviation	0.519	0.401
Average Force	0.00495	0.00266
TT_wrist_average	0.293	0.293

The dependent variable FR-30 can be predicted from a linear combination of the independent variables:

	P
FR_Baseline	<0.001
Gender	0.742
Age	0.355
BMI	0.744
Typing Speed	0.730
Peak wrist flexion	0.041
Peak wrist ulnar deviation	0.185
Average Force	0.913
TT_wrist_average	0.256

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict FR-30 ($P < 0.05$): FR_Baseline , Peak wrist flexion

Normality Test: Passed ($P = 0.417$)

Constant Variance Test: Passed ($P = 0.289$)

Power of performed test with alpha = 0.050: 1.000

Multiple Linear Regression Tuesday, November 29, 2011, 4:42:10 PM

Data source: FINAL ANALYSES in Keyboarding Data

FR-60 = 0.465 + (0.508 * FR_Baseline) + (0.0624 * Gender) - (0.00809 * Age) - (0.00973 * BMI) + (0.0117 * Typing Speed) + (0.0229 * Peak wrist flexion) + (0.00764 * Peak wrist ulnar deviation) - (0.0766 * Average Force) + (0.111 * TT_wrist_average)

N = 35 Missing Observations = 1

R = 0.757 Rsqr = 0.573 Adj Rsqr = 0.419

Standard Error of Estimate = 0.514

	Coefficient	Std. Error	t	P	VIF
Constant	0.465	0.924	0.504	0.619	
FR_Baseline	0.508	0.134	3.783	<0.001	1.390
Gender	0.0624	0.216	0.289	0.775	1.543
Age	-0.00809	0.0158	-0.514	0.612	1.404
BMI	-0.00973	0.0210	-0.464	0.646	1.174
Typing Speed	0.0117	0.0102	1.149	0.261	1.623
Peak wrist flexion	0.0229	0.0105	2.169	0.040	1.280
Peak wrist ulnar deviation	0.00764	0.0103	0.745	0.463	1.386
Average Force	-0.0766	0.0883	-0.868	0.394	1.276
TT_wrist_average	0.111	0.0553	2.008	0.056	1.239

Analysis of Variance:

	DF	SS	MS	F	P
Regression	9	8.835	0.982	3.722	0.004
Residual	25	6.594	0.264		
Total	34	15.428	0.454		

Column	SSIncr	SSMarg
FR_Baseline	6.323	3.775
Gender	0.0145	0.0221
Age	0.129	0.0696
BMI	0.00836	0.0569
Typing Speed	0.141	0.348
Peak wrist flexion	0.963	1.241
Peak wrist ulnar deviation	0.0214	0.146
Average Force	0.171	0.199
TT_wrist_average	1.063	1.063

The dependent variable FR-60 can be predicted from a linear combination of the independent variables:

	P
FR_Baseline	<0.001
Gender	0.775
Age	0.612
BMI	0.646
Typing Speed	0.261
Peak wrist flexion	0.040
Peak wrist ulnar deviation	0.463
Average Force	0.394
TT_wrist_average	0.056

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict FR-60 ($P < 0.05$): FR_Baseline , Peak wrist flexion

Normality Test: Passed ($P = 0.499$)

Constant Variance Test: Passed ($P = 0.298$)

Power of performed test with alpha = 0.050: 1.000

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