We approve the thesis of Hyunkook Jang.

Andris Freivalds
Professor of Industrial Engineering
Thesis advisor
Chair of Committee

M. Jeya Chandra
Professor of Industrial Engineering

Vladimir Zatsiorsky
Professor of Kinesiology

Milind J. Kothari
Associate Professor of Neurology, College of Medicine

Richard Koubek
Professor of Industrial Engineering
Head of the Department of Industrial and Manufacturing Engineering
ABSTRACT

The effects on nerve conduction measures of forceful exertion and repetitive movement with awkward wrist posture were examined with fifteen participants over 3 hours duration of exposure. Wrist workload was measured by using force resistance sensor and electrogoniometer, while the nerve conduction measures were recorded with TECA TD-20 EMG machine on before the start of the task and every 20 minutes thereafter, where the subject performed repetitive flexion/extension movements accompanied by intermittent pinch force exertion.

The results indicated that initial peak latencies (time = 0) were similar across workload conditions, however exposure to wrist workload over three hours of task performance produced a noticeable difference. Peak latencies for low force-low repetition (LOF.LOR), high force-high repetition (HIF.LOR), and low force-high repetition (LOF.HIR) conditions increased, while little change was found for high force-high repetition (HIF.HIR) condition. Regression analysis indicated that peak latency approached a reference value diagnostic of clinical evidence of carpal tunnel syndrome with 67 minutes of task performance, and 67 percent of participants had temporary peak latency increases beyond reference value under low force-low repetition (LOF.LOR) condition.

Thus, the high force-high repetition condition (HIF.HIR) results might be contrary to what would be expected, because full range of motions was not attained as supported
by highly significant correlation between peak latency change and the range of motion. Also, temperature gain derived from rapid repetitive movements and highly forceful exertions may counteract the prolongation of peak latency, and mask the developing effect of carpal tunnel syndrome.

As expected, skin temperature had a profound effect on nerve conduction measures. After correction for skin temperature, temperature-corrected peak latency over time produced similar results to the measured peak latency.

Correlation analyses between workload variables and peak latency indicated that maximum wrist flexion, maximum range of motion, and cumulative exposure time had highly significant relationships with peak latency over time. Among these relationships, especially, the most interesting correlation was presented between cumulative exposure time of wrist F/E angle > 30° and sensory nerve peak latency (r=0.3715, p=0.005), where peak latency increased as the cumulative exposure time increased. Regression analysis indicated that if wrist deviation repetitively exceeded 30° for over 125 minutes, sensory median nerve impairment may approach diagnostic clinical evidence of CTS. Thus, this relationship may be the most important output of this study, since peak latency change can be explained by cumulative time factor as well as wrist angular deviation factor, and it can be easily measured with the time interval when wrist is deviated over a threshold angle. In fact, the cumulative time of F/E angle > 30° may serve as the best measure for investigating the effects of dynamic wrist workloads on the nerve conduction, hence the prevalence of CTS.
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Chapter 1

INTRODUCTION

1.1 Problem Statement

Carpal tunnel syndrome (CTS) is the most commonly reported median nerve entrapment within carpal tunnel at wrist, resulting in changes of nerve conduction and symptoms that include numbness in fingers, pain in gripping, tingling at the hand, decreased grip strength, reduced object control precision, and nocturnal awaking (Kouyoumdjian et al., 2002; Werner et al., 2001; Levine et al., 1993; Nathan and Keniston, 1993; Bleecker et al., 1985). Currently accepted diagnostic method for assessing CTS is to perform nerve electrophysiological function testing, which is also calling nerve conduction studies, on the median sensory and/or motor nerve at wrist and hand. Slowed nerve conduction results in a positive diagnosis for CTS.

Most recent statistics from the Bureau of Labor Statistics (BLS), U.S. Department of Labor (2001) indicate that disorders associated with repeated trauma, including carpal tunnel syndrome have significantly increased in number of cases and as percentage of total occupational illness reported over the past two decades as shown in Figure 1.1. The repeated trauma disorders account for 67 percent of all occupational illness in 2000, which represents 241,800 reported new cases. However, many researchers believe that
the BLS figures underrepresent the total number of occupational illness in the workplace as many injured ill workers fail to report their ailments for fear of losing their jobs, promotions or benefits. Consequently, the statistics often used as indicators rather than absolute values (Silk, 1993).

Figure 1.1 Disorders associated with repeated trauma as a percentage of total occupational illness in private industry.
During the past two decades, numerous researchers have reported that extreme posture, repetitive motions, forceful exertions, rapid wrist movements, concentrated pressures, cold temperature, and prolonged vibration, etc., are associated with the risk of CTS (Werner et al., 2001; NIOSH, 1997; Hagberg et al., 1995; Ayoub, 1990a, 1990b, 1990c; Silverstein et al., 1986; Silverstein et al., 1987). The work-relatedness of the CTS is also supported by its higher industry incidence rate of 1.74 per 1,000 full time workers than the prevalence rate of 1.25 per general individuals (Franklin et al., 1991; Stevens et al., 1988). More specifically, Silverstein et al. (1996) reported that the incidence rate of CTS depends on the severity of occupational risks in the workplace citing a much higher incidence rate of meat packing industry, ranging 18 to 26 per 1,000 full time workers, in which most jobs require repetitive forceful wrist movements.

Insurance companies have reported that the percentage of worker's compensation costs related to work-related CTS has quadruped since 1987 (Silk, 1993). It is estimated that the average cost of surgical treatment for CTS was $10,000 per case with a range of $5,000 to $20,000 (Cobb et al., 1996). The total cost will increase if other expense items such as product loss, rehabilitation expense, employee absenteeism, and employee training, and etc, are included. Due to considerable cost, determining whether the CTS of worker is developed from occupational factors or non-occupational factors becomes a sensitive issue in the context of worker's compensation.

Although previous epidemiological studies have provided necessary qualification of associated risk factors, no clear dose-response relationship has yet been determined
between the amount or severity of works and the incidence or severity of the CTS (Gross et al., 1998; Hadler, 1997; Katz, 1994).

Research into causative factors associated with carpal tunnel syndrome has, up to, primarily focused on epidemiological surveys of OSHA 200 logs and similar workplace injury records. Such studies have been invaluable in identifying physical agents as posture, repetition, force that are believed to contribute to the disorder. However workplace injury records in these studies were typically derived based on employee self-reporting and are therefore likely to present a poor definition of the problem. Because nerve conduction studies on hand and wrist is a standard method for assessing CTS, the study of risk factors and median nerve function can warrant quantifying the dose-response relationship between contributory risk factors and CTS prevalence.

1.2 Current Work in This Area

1.2.1 Risk Factors versus CTS

The relationship between the three most cited occupational factors, wrist posture, repetition and force, and CTS has been reported often in the literature. Except for a few notable studies (Armstrong et al., 1982; Silverstein et al., 1986, 1987), the context of this relationship has been qualitative and inconclusive by epidemiological data. In Silverstein et al. (1986, 1987) studies, a gross dose-response relationship was established between dichotomous levels of repetition and force, and incidence rate of CTS, and cumulative
trauma disorders (CTDs) overall. These investigators found that odds ratios for risk of CTS and CTDs were 1.9 and 3.6, respectively, in high repetition jobs compared to jobs that requires a low number of repetitions. Also, the odds ratios for risk of CTS and CTDs for high force jobs compared to low force jobs were 1.8 and 4.9, respectively. Based on these results, they concluded that workers in jobs that required highly repetitive motions and forceful exertions were at a significantly greater risk of developing CTS than their counterparts in low repetitive and forceful jobs.

Unlike static wrist posture, however, repetition involves the dynamic components of angular velocity and acceleration, which could contribute to CTS and CTD risks. (Marras and Schoenmarklin, 1990; Schoenmarklin and Marras, 1993). However Silverstein’s et al. research did not consider the dynamic components that comprise repetitious wrist motions. The dynamic aspects of wrist motion must be explored because the tendon force, which is a risk factor of CTS, is affected by acceleration. Based on Newton's second law, the tendon force is proportional to wrist acceleration (F=M×A).

Marras and Schoenmarklin (1991) conducted an investigation into relationship between occupational risk factors including dynamic components, and CTS and CTDs incidence in industry setting. Wrist motions measures including wrist posture, velocity and acceleration were recorded using an electromechanical goniometer, which monitored wrist activities in the flexion/extension, ulnar/radial deviation and pronation/supination planes. These data were classified based upon low, median, and high levels of wrist activities. Incidence of self-reported CTS among participant was then mapped against
recorded wrist motions. Their results suggested that the mean flexion/extension acceleration values of high and low CTS risk group can serve as preliminary benchmarks to establish injuries and safe levels of wrist motion in industry using logistic regression. The investigators found that self-reported risk of developing CTS increased by 600 percent when wrist flexion/extension acceleration exceeded $824 \degree/sec^2$, compared with exposures less than $490 \degree/sec^2$.

1.2.2 CTS versus Nerve Conduction Study

Currently, the only reliable technique for assessing the severity of CTS is the nerve conduction studies (Ghavanin and Haghigh, 1998; Katz, 1994; Jackson and Clifford, 1987; Stevens, 1987; Kimura, 2001; Burnham and Steadward, 1994, Melvin et al., 1973; Kembel, 1968). Most patients should be referred for nerve conduction studies if the diagnosis is suspected.

Electromyography (EMG) system quantifies nerve conduction parameters, which include latency, amplitude, duration and conduction velocity, by measuring the time required for an impulse to travel from a stimulus site to a more proximal or distal site at which a motor or sensory response of the nerve is evoked. Results are compared against reference values, which have been established for both healthy and symptomatic populations. Median motor nerve latency has been shown to be prolonged, and/or median motor nerve amplitude has been shown to be decreased in cases of patients with CTS
compared with normal subjects (Kimura, 2001 and 1979; Thomas, 1960; Simpson, 1956). Also, patients with CTS demonstrate a prolonged median sensory nerve latency and/or decreased amplitude, and/or reduced conduction velocity compared to normal subjects within wrist (Stevens, 1987; Felsenthal and Spindler, 1979; Kimura and Ayyar, 1985; Kemble, 1968). The electrodiagnostic evaluation has been widely instituted and is now used as the standard for the early detection of peripheral nerve disorders.

1.2.3 Research Voids in This Area

There is general agreement among researchers that occupational risk factors including awkward posture, repetitive motions, and forceful exertions, cause a possible etiology for carpal tunnel syndrome, and nerve conduction studies within the wrist are now the only reliable technique for assessing CTS. However, there are few research studies investigating the relationship between the occupational risk factors and the median nerve function. This relationship could verify the dose-response relationship directly between occupational risk factors and prevalence of CTS.

Marin et al. (1983) conducted a study to demonstrate the effect of wrist flexion and extension on median nerve function, which includes motor and sensory nerve latencies, to improve the sensitivity of nerve conduction studies for CTS in clinical field. Using a device to enable the wrist to be held in extreme tolerable flexion, ranging 65 to 90 (mean 82) degrees, or extension, ranging 60 to 80 (mean 77) degrees, motor and
sensory nerve latencies of median nerve were obtained following wrist flexion and extension for 5 and 10 minutes. The results showed an increase in distal latencies for both normal and CTS patients groups. The highest percentage increment occurred in sensory latency of wrist flexion in the CTS patients.

In a similar study, Dunnan and Waylonis (1991) investigated the effects of wrist flexion on median motor and sensory evoked potential latencies in much larger group of 87 subjects including 19 patients with CTS. The wrist was held in position of extreme tolerable flexion, approximately 90 degrees, using a large rubber band that was stabilized around the elbow for 5 minutes. The results showed a slight prolongation of median motor nerve latency (0.06 ± 0.1 msec) and sensory nerve latency (0.03 ± 0.05 msec).

Although these two studies have shown a possibility of finding the relationship between static awkward wrist postures and median nerve function, the main purpose of their studies aimed to enhance the accuracy of nerve conduction studies in mild and borderline cases of CTS using sustained wrist flexion period before nerve function testing, not to investigate exclusively the relationship between them.

Unlike previous two studies, Lloyd (1999) tried to investigate the relationship between the median nerve function and repetitive wrist motions in lab environment. Subjects were asked to perform continuous repetitive motions of the wrist in flexion/extension plane with four levels of wrist acceleration defined as control, low, moderate and high wrist repetitions. The results showed that the angular acceleration of
the wrist presented the significant association with nerve conduction, where nerve conduction decreased as wrist acceleration increased.

Although his study provided a relationship between repetitious wrist motion and nerve function, he did not consider another important risk factor, forceful exertions in his study. Most tasks require some degree of force to hold loads or hand tool and tasks that require forceful exertion place mechanical stress on the muscles, tendons, nerves, ligaments and joints (Armstrong and Chaffin, 1979a; Silverstein et al., 1986; Silverstein et al., 1987). Roquelaure et al. (1997) indicated that exertion of force over 1 kg was associated with 9.0 odds ratio for prevalence of CTS. Also, the odds ratios for jobs with high force requirements compared with the low force jobs were large as much as the high repetition jobs compared to low repetition jobs. Therefore, we should include exclusively the three most cited risk factors, awkward posture, forceful exertions, and repetitive motions when investigating the relationship between prevalence of CTS and nerve conduction studies. The purpose of this research study is to develop the dose-response relationship between nerve conduction function and dynamic wrist workloads including forceful exertion and repetitive movement with awkward posture.

1.3 Hypothesis and Research Objectives

The principle hypothesis of this study is based on the premise that median nerve function decreases as wrist workloads increase. Also, if changes in nerve function can be
indicative of the development of carpal tunnel syndrome, the changes observed during the dynamic workloads could confirm the concept of dynamic carpal tunnel syndrome.

This study proposes to demonstrate if a measurable change in median nerve function can be systematically produced with exposure to dynamic wrist workloads. If achieved, this facilitates the development of quantitative dose-response relationship between occupational risk factors and CTS prevalence. Also this facilitates the establishment of threshold limit values for occupational risk factors of forceful exertions and repetitive motions for preventing CTS.

The objectives of this research can be summarized as follows;

(1) Determine if there is relationship between a measurable change in median nerve function and the exposure to dynamic wrist workloads that include forceful exertions and repetitive motions with awkward posture.

(2) If achieved, develop the dose-response relationship between the occupational risk factors and nerve conduction measure, and suggest the best measure for investigating the effects of dynamic wrist workloads on the nerve conduction, hence the prevalence of CTS.

(3) Develop threshold limits for occupational risk factors for preventing incidence of CTS.
1.4 Organization of the Proposal

This proposal is organized into eight chapters. In Chapter 1, the importance of research on carpal tunnel syndrome is overviewed and current research work and research voids in this area are described. In addition, the research hypothesis and objectives are provided.

Chapter 2 presents a detailed review of the background literature related to carpal tunnel syndrome (CTS). It consists of the anatomical understanding of hand, work-related musculoskeletal disorders, anatomy of carpal tunnel, median nerve, risk factors associated CTS, wrist dynamics, and pathophysiological mechanism of CTS. Chapter 3 describes the diagnostic methods of CTS, and background literature for nerve conduction studies such as stimulating and recording of median nerve, electrode placements, nerve conduction parameters, normal values for median nerve conduction, and standard measurement methods.

In Chapter 4, the measurement systems for this study are described. The general characteristics of force sensors and electrogoniometers for monitoring and measuring workloads are presented, and the results of reliability and performance test are provided. In addition, the characteristic and performance of the EMG system for nerve conduction studies is presented.

Chapter 5 presents the experimental methods and experimental design including workload conditions, subject sampling and recruitment and data collection procedure.
The experiment was conducted to demonstrate if a measurable change in median nerve function can be presented with exposure to dynamic wrist workloads.

Chapter 6 presents experimental results and analyses. Chapter 7 presents interpretations and discussion of these results with considerations to limitations of the study. Chapter 8 presents a conclusion. The appendices provide supplemental information. Appendix A contains the participants’ informed consent form, and Appendix B includes the screening questionnaire.
Chapter 2

LITERATURE REVIEW - CARPAL TUNNEL SYNDROME

2.1 Anatomy of Hand and Wrist

The hand is a complex anatomical system of static and dynamic structures. The anatomy of the hand is efficiently organized to carry out a variety of complex tasks. This section describes the musculoskeletal structure of the hand and wrist to provide understanding of carpal tunnel syndrome (CTS).

2.1.1 Skeleton of Hand

The upper limb skeletal system consists of thirty-two bones, twenty-seven of which are found in the hand and wrist, comprising of 8 carpal bones, 5 metacarpal bones and 14 phalanges. These 27 bones form the solid framework of the hand. They are united at the joints by ligaments and are arranged to contribute to hand definitions and provide attachment for muscles by which the various movements are accomplished (Palastanga et al., 1994; Kapit and Elson, 1993; Berger and Garcia-Elias, 1991). Figure 2.1 shows the skeletal structure of the hand.

The carpal bones are irregularly sharped and each is approximately the size of a marble. They arranged in two irregularly shaped rows of four bones each. The proximal
row contains the scaphoid, lunate, triquetral, and pisiform, and the distal row contains the trapezium, trapezoid, capitate, and hamate. The bones are bound together by numerous intercarpal ligaments and interosseous intercarpal ligaments. Anatomically, the wrist (or carpus) is the articulation of the radioulnar junction with the scaphoid and lunate (Spence, 1990). The wrist has three axes of movement or degrees of freedom.

Figure 2.1  Skeletal of the hand  
(adapted Kapit and Elson, 1977)
Five metacarpal bones form the skeletal of the palm of the hand. The metacarpals are numbered that the metacarpal bone of thumb is numbered 1, and that of little finger is numbered 5. The general shape of the metacarpal is a shaft with two extremities: base (carpal extremity), and head (phalangeal extremity). The base of each metacarpal articulates with the distal row of the carpal bones. The phalanges, two in the thumb and three in each finger, are numbers from proximal to distal: 1 (proximal), 2 (middle), 3 (distal). The joints between the phalanges of every fingers are hinge joints with roughly cylindrical articular surfaces and singles axis of rotations.

2.1.2 Hand Joints

Joints are also important areas to be considered in hand movement. They mainly consist of carpal joint, metacarpal joint, and finger joint. Radio-carpal joint is formed by the distal end of the radius proximally and the proximal row of the carpus (scaphoid, lunate and triangular) distally. This joint has two degrees of freedom, flexion/extension and radial and ulnar deviation. All movements of this joint are combined with those of the intercarpal joint, and the combined radiocarpal and intercarpal articulations allow 170 degrees of excursion range in flexion/extension direction and approximately 80 degrees of range in radial/ulnar deviations directions (Tubiana, 1981).

Metacarpophalangeal (MP) joints consist of simple and spheroidal diarthrosis and their major movement is a combination of gliding and rolling. The volar ligaments of
these joints help to restrict hyperextension and prevent impingement. The movements permitted at this joint are flexion/extension, abduction/adduction, and circumduction. The range of the flexion/extension movement is about 110 to 120 degrees (90 degrees for flexion and 20 degrees for extension) and the range of the lateral movement is about 40 to 60 degrees.

Interphalangeal (IP) joints are true hinge joints having one degree of freedom. Each finger has two IP joints (proximal and distal), whereas the thumb has only one IP joint. The excursion ranges of flexion/extension direction in the proximal IP and distal IP joint are approximately 110 to 130 degrees and 45 to 90 degrees, respectively (Steindler, 1955).

### 2.1.3 Hand Muscles

Movements of the hand are accomplished by contraction of muscle-tendon units located in the forearm and hands. The muscles are divided into two groups, extrinsic and intrinsic, based on an origin of the muscles. The extrinsic muscles are originated from the forearm while the intrinsic muscles are entirely confined to the hand. Therefore, extrinsic muscles are long and provide strength, while intrinsic muscles are short and provide precise coordination of the fingers.

Extrinsic muscles of the hand are divided into two groups based on location and function. The muscles of the anterior group serve as flexors. Most of these anterior
muscles have their origins on the medial epicondyle of the humerus and insert on the
carpal, metacarpals or phalanges via corresponding tendons. The muscles of the posterior
group serve extensors. Most of these posterior muscles have their origins on the lateral
epicondyle of the humerus and insert on the metacarpals or phalanges via corresponding
tendons. Both the anterior and posterior groups can be divided further into superficial and
deep muscles. The tendons of these forearm muscles are held down at the wrist by flexor
and extensor retinacula. (Spencer, 1990). Intrinsic muscles whose origin and insertion are
both in the hand make possible the fine and precise movements that are typical of the
fingers. They are divided into three groups: the thenar, the hypothenar and midpalmar
muscle groups acting on the thumb, on the little finger, and on the all phalanges except
the thumb, respectively. Figure 2.2 shows the hand muscles, and the locations and actions
of extrinsic and intrinsic muscles are listed in Table 2.1 and Table 2.2.
Figure 2.2 Muscles of the hand
(adapted from Higgins and Mandiberg, 2000)
Table 2.1 Extrinsic muscles of the hand and wrist  

<table>
<thead>
<tr>
<th>Group</th>
<th>Layer</th>
<th>Name</th>
<th>Abbrev.</th>
<th>Nerve Supply</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior</td>
<td>Superficial</td>
<td>Flexor carpi radialis</td>
<td>FCR</td>
<td>Median</td>
<td>Flexes and abducts the hand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Palmaris longus</td>
<td>PL</td>
<td>Median</td>
<td>Flexes hand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flexor carpi ulnaris</td>
<td>FCU</td>
<td>Ulnar</td>
<td>Flexes and adducts hand</td>
</tr>
<tr>
<td>Middle</td>
<td></td>
<td>Flexor digitorum superficials</td>
<td>FDS</td>
<td>Median, C7, C8, T1</td>
<td>Flexes phalanges and hand</td>
</tr>
<tr>
<td>Deep</td>
<td></td>
<td>Flexor digitorum profundus</td>
<td>FDP</td>
<td>Median, Ulnar, C7, C8, T1</td>
<td>Flexes phalanges and hand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flexor pollicis longus</td>
<td>FPL</td>
<td>Median, C8, T1</td>
<td>Flexes thumb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extensor carpi radialis longus</td>
<td>ECRL</td>
<td>Radial</td>
<td>Extends and abducts hand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extensor carpi radialis brevis</td>
<td>ECRB</td>
<td>Radial</td>
<td>Extends hand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extensor digitum communis</td>
<td>EDC</td>
<td>Radial</td>
<td>Extends fingers and hand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extensor digit minimi</td>
<td>EDM</td>
<td>Radial</td>
<td>Extends little finger</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extensor carpi ulnaris</td>
<td>ECU</td>
<td>Radial</td>
<td>Extends and adducts hand</td>
</tr>
<tr>
<td>Posterior</td>
<td>Superficial</td>
<td>Abductor pollicis longus</td>
<td>APL</td>
<td>Radial, C6, C7</td>
<td>Extends thumb and abducts hand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extensor pollicis brevis</td>
<td>EPB</td>
<td>Radial</td>
<td>Extends thumb and abducts hand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extensor pollicis longus</td>
<td>EPL</td>
<td>Radial</td>
<td>Extends thumb and abducts hand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extensor indicis</td>
<td>EI</td>
<td>Radial</td>
<td>Extends index finger</td>
</tr>
</tbody>
</table>
Table 2.2 Intrinsic muscles of the hand and wrist

<table>
<thead>
<tr>
<th>Intrinsic Muscles</th>
<th>Nerve Supply</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group</td>
<td>Name</td>
<td>Abbrev.</td>
</tr>
<tr>
<td>Thenar muscles</td>
<td>Abductor pollicis</td>
<td>AbPB</td>
</tr>
<tr>
<td>brevis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opponents pollicis</td>
<td>OP</td>
<td>OP</td>
</tr>
<tr>
<td>Flexor pollicis brevis</td>
<td>FPB</td>
<td>FPB</td>
</tr>
<tr>
<td>Adductor pollicis brevis</td>
<td>AdPB</td>
<td>AdPB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hypothenar muscles</td>
<td>Palmaris brevis</td>
<td>PB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abductor digiti minimi</td>
<td>ADM</td>
<td>ADM</td>
</tr>
<tr>
<td>Flexor digiti minimi brevis</td>
<td>FDM</td>
<td>FDM</td>
</tr>
<tr>
<td></td>
<td>Opponens digitii</td>
<td>ODM</td>
</tr>
<tr>
<td></td>
<td>minimi</td>
<td></td>
</tr>
<tr>
<td>Midpalmar muscles</td>
<td>Lumbricales</td>
<td>L</td>
</tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dorsal interossei</td>
<td>DI</td>
<td>DI</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palmar interossei</td>
<td>PI</td>
<td>PI</td>
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</tr>
</tbody>
</table>
2.2 Work-Related Musculoskeletal Disorders (WMSDs)

Work-related musculoskeletal disorders (WMSDs) refer to a category of physical signs and symptoms due to chronic musculoskeletal injuries where the causes appear to be related to some aspect of repetitive work. These disorders may also be referred to as 'cumulative trauma disorders (CTDs)', 'repetitive strain injuries (RSI)', 'repetitive motions injuries', or 'over use injuries' (Putz-Anderson, 1990). They may develop over a period of weeks, months, or even years due to prolonged mechanical stress imposed on the musculoskeletal system. These disorders develop gradually in such soft tissue structures as tendons, tendon sheaths, nerves, muscles or blood vessels. Moreover, these conditions are caused, accelerated or aggravated by repeated stresses. As with strains and sprains, common symptoms include local pain and swelling.

The WMSDs can be classified into three basic types from an anatomical view: tendon disorder, neurovascular disorder and nerve disorder.

Tendon disorders occur at or near the joints where the tendons irritate nearby ligament and bones. The most frequently noted symptoms are a dull aching sensation over the tendon, discomfort with specific movements and tenderness to touch. Recovery is usually slow and condition may easily become chronic if the cause is not eliminated (Lipscomb, 1959). The tendon disorders include Tendinitis, Tenosynovitis, DeQuervain's disease, Trigger finger, Gabglionic cyst, Tennis elbow, Golfer's elbow, and Rotator cuff tendinitis.
Neurovascular disorders involve the compression of both the nerves and adjacent blood vessels. The symptoms include tingling, numbness, and loss of fine control in the hand. Thoracic outlet syndrome, and Vibration hand syndrome are common examples of neurovasular disorders (Tyson et al. 1975)

Nerve disorders occur when repeated or sustained work activities expose the nerves to pressure from hard, sharp edges of the work surface, tools or nearby bones, ligaments, and tendons (Feldman et al., 1983). The symptoms include pain, tingling, and numbness in the hand. Carpal tunnel syndrome (CTS) is the most common nerve disorder.

2.3 Carpal Tunnel Syndrome

Muscles are attached to the skeleton by tendons, and most of the muscles that operate the hand are found in the forearm. Consequently, there are many long tendons running from the forearm muscles to the bones in the hand. As these muscles contract to bend the fingers, tendons slide through the wrist. These tendons are protected by synovial sheaths which contain fluid to aid lubrication. This structure is illustrated in Figure 2.3.

When the wrist tendons became irritated and swollen, the resulting compression on the median nerve impairs the sensory and motor function of the hand (NIOSH, 1989). The nerve compression also can be induced by wrist fractures, rheumatoid arthritis, tumors and diabetes mellitus. The increased pressure in the carpal tunnel can trap and/or
pinch the median nerve, causing occupational numbness, pain and tingling in the thumb, index and middle fingers. This condition is called carpal tunnel syndrome. In the context of worker's compensation, CTS is increasingly being claimed as a work-related injury (Katz, 1994).

Figure 2.3 Anatomy of hand and wrist
(Source: Adapted from Hitchcock and D'Silva, 2000)
2.3.1 Anatomy of Carpal Tunnel

The carpal tunnel is a tunnel-like structure in the wrist which is enclosed by the eight carpal bones and by the inelastic flexor retinaculum, also known as the transverse carpal ligament. Nine tendons, which control finger movements, including four tendons of the flexor digitorum superficialis (FDS), and four tendons of the flexor digitorum profundus (FDP) and one tendon of the flexor pollicis longus (FPL), and the median nerve which enervates the thumb, index and ring fingers, pass through the tunnel from the forearm to the hand (Katz, 1994; Tayyari and Emanuel, 1993). The structure of carpal tunnel is illustrated in Figure 2.4.

Figure 2.4 Anatomy of carpal tunnel
(Source: Higgins and Mandiberg, 2000, and Medical multimedia group, 1998)
Cross-sectional area of the carpal tunnel is smallest 2.0 to 2.5 cm distal to proximal entrance of the tunnel, where it rigidly bound on by carpal bones and the transverse carpal ligament (Robbins, 1963). Although the carpal tunnel is not a closed compartment, it often functions as a confined space. Because of its particular anatomy, there is normally little free space and any physiologic or pathologic process that reduce its capacity or increases the volume of its contents can increase interstitial pressures (Cobb et al., 1992).

Although a wide variety of conditions may predispose a person to CTS, non-specific synovial proliferation within the carpal tunnel is the most common cause (Stevens et al., 1992). Repetitive flexion or extension of the wrist may predispose persons to CTS. Flexion of the wrist causes the flexor tendons in the fingers to be displaced against the palmer side of the carpal tunnel, producing pressure on the both tendons and the median nerve. Extension of the wrist causes the tendons to be displaced against the dorsal side of the tunnel and radial head, again producing increased pressure. Carpal tunnel pressures have been measured by transducers inserted within the canal, and they can be markedly higher in symptomatic patients than in control subjects, and rise markedly during flexion or extension (Gelberman et al., 1981).
2.3.2 CTS and its Work-Relatedness

Carpal tunnel syndrome is divided into acute and chronic depending on its relative duration to develop symptoms from nerve conduction abnormality. The acute case is relatively rare and developed within a short period due to acute compression to the median nerve followed by the abnormal clinical conditions: spontaneous bleeding in hemophiliacs, persistent thrombosis of the median artery, dislocation of the carpal tunnel base, infections, fractures, or during pregnancy (Gelberman et al., 1988). On the other hand, the chronic case induces such pathophysiological changes at the hand and wrist as nerve impairment and muscle atrophy after a long period from exposure to hazard conditions.

It is so important to determine if the symptoms and signs of a worker with CTS are associated with his/her work due to the cost and benefits from worker's compensation system. If the case is work-related, the compensation system will redeem all costs accompanied to treatment and lost salaries. However, no clear quantitative dose-response relationship between occupational risk factors and CTS prevalence has been yet established.

NIOSH provides a set of criteria, including clinical symptoms, objective signs, and evidence of work-relatedness as practical guidelines to define a case of work-related CTS as shown in Table 2.3. If a person reports one or more of symptoms, and he/she shows a positive clinical diagnosis result, he/she is considered as CTS patients.
Moreover, if the patient involved a job with one or more of ergonomic hazards, then the case is determined as work-related CTS.

Table 2.3 NIOSH case definition criteria for work-related CTS
(Adapted from Burnham and Steadward, 1994; Hales and Bertsche, 1992; and Franklin et al., 1991)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symptoms</td>
<td>A patient reports one or more of the following symptoms in the hand:</td>
</tr>
<tr>
<td></td>
<td>- pain</td>
</tr>
<tr>
<td></td>
<td>- numbness</td>
</tr>
<tr>
<td></td>
<td>- paresthesias (tingling sensation)</td>
</tr>
<tr>
<td></td>
<td>- hypoesthesia (loss of sensation)</td>
</tr>
<tr>
<td>Clinical</td>
<td>The patients should show a positive result either in</td>
</tr>
<tr>
<td>diagnosis</td>
<td>- physical provocative tests (Tinel's test and Phalen's maneuver)</td>
</tr>
<tr>
<td></td>
<td>- nerve conduction test.</td>
</tr>
<tr>
<td>Evidence of work-relatedness</td>
<td>The patients should involve a job with one or more of the following ergonomic hazards:</td>
</tr>
<tr>
<td></td>
<td>- repetitive and/or prolonged motions of the hand</td>
</tr>
<tr>
<td></td>
<td>- forceful exertions by the hand including pinching or gripping</td>
</tr>
<tr>
<td></td>
<td>- sustained awkward wrist postures</td>
</tr>
<tr>
<td></td>
<td>- excessive vibration transmitting of the hand</td>
</tr>
<tr>
<td></td>
<td>- localized mechanical pressure over the wrist or base of the palm</td>
</tr>
<tr>
<td></td>
<td>- cold work environment</td>
</tr>
</tbody>
</table>

2.4 Median Nerve

Three nerves, radial, median and ulnar, named with reference to their anatomical location, pass through the wrist. Typically, each of these nerves provides motor and sensory function to a specific area of the hand. The radial nerve is directed toward the
proximal edge of the thumb. The median nerve serves the distal edge of the thumb, second and third digits, and radial side of the fourth digit. The ulnar nerve innervates to the ulnar side of the fourth digit and the fifth digit.

Figure 2.5 Digital branches of median and ulnar nerves on hand
(adapted from Rosenbaum and Ochoa, 1993)
Three branches of the median nerve develop within or just distal to the wrist. Within tunnel, the median nerve divides into a motor branch that innervates the thenar muscles, including the abductor pollicis brevis (AbPB), the opponents pollicis (OP) and the superficial head of the flexor pollicis brevis (FPB), and distal sensory branches that supply the thumb, index, and middle fingers, and the radial half of the ring finger. Finally, anastomotic fibers provide communication between the median and ulnar digital sensory distribution. The digital branches of median nerve and ulnar nerve are illustrated in Figure 2.5.

Peripheral nerves such as median and ulnar, comprise three basic tissue elements: axons (neuron) which transmit signals between the central nerve system and receptors, myelin sheaths (interstitial elements) and connective tissues. The three major elements respond differently to trauma, which can increase nerve pressure, reduce microcirculation and produce edema, resulting in local nerve ischemia and inhibiting nerve function (Pfalzar and McPhee, 1995).

An action potential to transmit signals is normally initiated by excitatory activity of the generator potentials activating the trigger zone of the neurons, namely, an integrated potential. The integrated potential produces a depolarization of the plasma membrane by a rapid increase in the sodium ion (Na\(^+\)) current. In depolarization there is the trust to decrease the membrane polarization, thereby making the region inside of the membrane more positive with respect to tissue fluid outside the cell membrane (Noback, 1981). The action potential of nerve fiber along axon is propagated in a jumping manner
from a node to another node in a neuron with a myelinated axon or continuous spread in a neuron with an unmyelinated axon as seen in Figure 2.6. The minus (-) sign within the neuron signify negativity with respect to the extracellular fluid outside the neuron. The current flows from a region of positive potential to a negative potential. The axon transfer mechanisms may be disturbed by increased pressure to the nerve fiber, which is a pathological condition of entrapment neuropathy (Hagberg et al., 1995).
2.5 Carpal Tunnel Pressure

Carpal tunnel pressure is an important factor in the pathophysiology of CTS, although the evidence linking persistent elevated pressure to the development of CTS is indirect. Patients with CTS showed elevated carpal tunnel pressure compared with healthy control subjects where mean pressures are 26 mmHg and 13 mmHg, respectively (Weiss et al., 1995; Luchetti et al., 1990). Luchetti et al. (1990) also identified a correlation between carpal tunnel pressure and nerve conduction. The reduction in sensory conduction velocity was greatest in the distal portion of the carpal tunnel where the pressure was highest. Increased carpal tunnel pressure can produce short-term sensory and motor nerve conduction deficits and elicit the symptoms of median neuropathy.

Extreme wrist postures, tendon forces and external pressures increase carpal tunnel pressure, and these factors associated with development of CTS in epidemiological studies (Keir et al., 1997; Keir et al., 1998a; Keir et al., 1998b; Gelberman et al., 1981; Werner et al., 1983). Highest pressures as a result of wrist posture were found in extreme extension conditions, which continue to rise to an indeterminate maximum if the position is maintained (Keir et al. 1997; Luchetti et al, 1998). Carpal tunnel pressures as high as 94 mmHg and 110 mmHg have recorded in CTS patients in extreme flexion and extension, respectively.

Fingertip pressing and pinching tasks produce large carpal tunnel pressure for relatively low external forces (Keir et al., 1998b). Moreover, internal loading induced during pinching tasks is near twice that of fingertip pressing tasks for identical external
forces, where use of pinch hand postures can result in up to 50 percent more force in the first and second flexor tendons adjacent to the median nerve (Chao, 1976; Smith et al., 1977). Deviations of the wrist and metacarpal joints further increase pressure as a function of posture dependent tendon strain (Keir et al., 1998a; Rempel et al., 1998).

Externally applied mechanical pressures over various regions of the palmer surface of the hand and wrist have also produced elevated carpal tunnel pressures leading to carpal tunnel syndrome (Cobb et al., 1995).

2.6 Risks Factors Associated with CTS

A risk factor is any attribute, experience or exposure that increases the probability of occurrence of a diseases or disorder. Specific risk factors of CTS are difficult to identify because many risk factors may interact simultaneously to bring about the condition (Hadler, 1990; Moore, 1992; NIOSH, 1997). Moreover, the interaction between risk factors may have a mutiplicative rather than an additive effect (Armstrong, 1994). It is also difficult to isolate occupational stressors from other risk factors including personal and psychosocial factors. Individual susceptibility further compounds the problems.

These risk factors are classified largely into two groups: occupational (physical) factors consisting of task and environmental conditions, and personal factors including age, gender, anthropometric factors and medical history.
2.6.1 Occupational Risk Factors

Activities associated with the development of CTS may arise from ordinary movements that include repetitive activities such as griping and reaching (Putz-Anderson, 1990). These movements may become hazardous if they are repeated in a forceful and awkward posture without sufficient rest or recovery time. The major risk factors include; forceful exertion, repetitive motions, awkward postures, localized contact stresses, vibration, and cold temperature (Armstrong, 1994; Hagberg et al., 1995; Keyserling et al., 1993; NIOSH, 1997).

2.6.1.1 Forceful Exertion

Most jobs require some degree of force to move loads, resist gravity, and stabilize the body. Manual tasks in manufacturing and production environments often require exertion of high pinch or grip forces on hand tools or workplaces, often within very short cycle times, amounting to thousands of forceful pinches per day (Kroemer, 1989).

Previous researchers have reported that the risk of CTS increases with an increase in forceful exertions (Armstrong and Chaffin, 1979a; Silverstein et al., 1987). Tasks that require forceful exertions place higher loads on the muscles, tendons, ligaments and joints. As muscle force increases in response to static and dynamic task loads, circulation within the muscle decreases, which accelerates development of localized fatigue (Pheasant, 1994; Chaffin, 1973). Based on CTS prevalence for active workers in high incidence jobs, Silverstein et al. (1986, 1987) reported that the odds ratios for risk of CTS
and CTDs for high force jobs compared to low force jobs were 1.8 and 4.9, respectively. Roquelaure et al. (1997) found that the odds ratio for forceful exertions increased to 9.0 for external forces greater than 1.0 kg.

2.6.1.2 Repetitive Motions

Numerous studies identified the repetitive motions as a risk factor associated with development of CTS (Roquelaure et al., 1997; Keyserling et al., 1993; Silverstein et al., 1987; Cannon et al., 1981). Many workers perform the same tasks and stereotyped motions over and over, sometimes thousands or tens of thousands time each day. Highly repetitive motions require fast muscle contractions, which become less efficient and demand greater recovery time because muscle capacity to produce force diminishes with increasing contraction speed.

Silverstein et al. (1987) reported that odds ratios for risk of CTS and CTDs were 1.9 and 3.6, respectively, in high repetition jobs compared to jobs that requires a low number of repetitions. Based on these results, they indicated that jobs which have a basic cycle time of 30 seconds or less, and jobs in which over 50 percent of the work cycle are spent performing the same basic motions pattern have been associated with elevated rates of CTS. Roquelaure et al. (1997) reported that odds ratio increase to 8.8 as cycle time for the shortest elementary operation is reduced to ten seconds.
2.6.1.3 Awkward Posture

Awkward posture is one of the most frequently cited risk factors for CTS (Armstrong, 1994; Hagberg et al., 1995; Armstrong, 1986, Armstrong and Chaffin, 1979a; Moore, 1992). Common examples of awkward wrist postures include excessive flexion, extension, radial and ulnar deviation, and pinch grips (Kibi and Mattila, 1991; Kilbom et al., 1986). Awkward postures overload muscles and tendons, loads joints in an asymmetric manner, thereby inhibiting blood flow (VanWely, 1970). The median nerve may be under considerable risk during awkward hand postures which place extreme pressure on the flexor tendon. In fact, sizable compressive forces have been demonstrated in the median nerve when hand movements involve simultaneous pinching and extreme wrist flexion (Rempel and Horie, 1994).

Based on data derived from the 1998 National Institute for Occupational Safety and Health (NIOSH) national health interview survey, in which incidence and exposures data for 127 million US workers was collected, Tanaka et al. (1995, 1997) reported that tasks involving bending and twisting of the wrist increase CTS prevalence by 520 to 550 percent.

2.6.2 Personal Risk Factors

Musculoskeletal disorders including CTS are not always work-related. These disorders can occur from recreational activities and can even occur with unknown cause (Nathan et al., 1992; Westgaard and Jansen, 1992).
In regards to gender effect on CTS, Nathan et al. (1992) reported that CTS is more common in females than males, with a ratio of 2 to 1 and it often occurs in middle aged females. Pregnancy, alteration in female ovarian hormone levels and use of oral contraceptive have been suggested as factors that may increase the risk of CTS in women (Cannon et al., 1981). Risk of CTS prevalence increases by three percent per aging year. Categorically, active workers over 40 years old are 20 percent more at risk than are younger workers (Stevens et al., 1988; Tanaka et al., 1988; Phalen, 1972).

The development of CTS have been related to the previous medical history (Putz-Anderson, 1990; Phalen, 1972; Tanaka et al., 1988) Several diseases or trauma such as chronic trauma, bone fracture, rheumatoid arthritis, bone disease, and hypertension were found in the medical history of CTS patients.

As for anthropometric factors, a small wrist or hand size has been suggested as a risk factor because the force per unit surface area on the median nerve during wrist deviations is higher for small wrists. Obesity as measured by a body mass index (BMI) was found to be significantly associated with an increased likelihood of having CTS (Nathan et al., 1992; Werner et al., 1994; Radecki, 1995). Specially, Werner et al. (1994) found that individuals whose BMI exceed 29 were 2.5 times more likely to be diagnosed with CTS than persons of BMI less than 20.
2.7 Wrist Dynamics and CTS

Wrist dynamics such as wrist velocity and acceleration is another important factor in the development of CTS. Several epidemiological studies have identified that highly dynamic wrist motions have a strong positive association with the prevalence of CTS (Hansson et al., 1996; Marklin and Monroe, 1998; Serina et al., 1999; Marras and Schoenmarklin, 1993; Schoenmarklin et al., 1994). Since the repetitive wrist movements can be broken into cyclic wrist motions with static position, dynamic angular velocity and acceleration components, an examination of this contributory factor could lead to a better understanding of the development of CTS. The dynamic aspects of wrist motion also are important in the etiology of CTS because tendon force is affected by wrist acceleration, and the relationship between acceleration and tendon force can be explained biomechanically by Newton's second law, force = mass × acceleration, and friction.

2.7.1 Dynamic Wrist Motions

The static components of the wrist joint typically include postural information such as position, and range of motion (ROM) measured in each plane of the wrist joint, while dynamic components of wrist typically include angular velocity and angular acceleration.

Several studies as shown in Table 2.4 have attempted to use the angular velocity and acceleration variable as potential risk factors in their epidemiological research.
Marras and Schoenmarklin (1993; Hansson et al., 1996; Marklin and Monroe, 1998; Serina et al., 1999).

Table 2.4 Wrist angular velocity and acceleration studies as risk factors

<table>
<thead>
<tr>
<th>Previous studies</th>
<th>Variable</th>
<th>Flexion/Extension</th>
<th>Radial/Ulnar</th>
<th>Pronation/Supination</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>Peak</td>
<td>Mean</td>
</tr>
<tr>
<td>Marras and Schoenmarklin</td>
<td>Position</td>
<td>High risk</td>
<td>-12.0</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low risk</td>
<td>-10.1</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>Angular velocity</td>
<td>High risk</td>
<td>42</td>
<td>174</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low risk</td>
<td>29</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>Angular</td>
<td>High risk</td>
<td>824</td>
<td>4,471</td>
</tr>
<tr>
<td></td>
<td>acceleration</td>
<td>Low risk</td>
<td>494</td>
<td>2,588</td>
</tr>
<tr>
<td>Hansson et al. (1996)</td>
<td>Position</td>
<td>Fish processing</td>
<td>-1</td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>Angular velocity</td>
<td>Fish processing</td>
<td>61</td>
<td>142</td>
</tr>
<tr>
<td>Marklin and Monroe (1998)</td>
<td>Angular velocity</td>
<td>Bone trimming</td>
<td>45</td>
<td>239</td>
</tr>
<tr>
<td></td>
<td>Angular</td>
<td>Bone trimming</td>
<td>844</td>
<td>4,895</td>
</tr>
<tr>
<td>Serina et al. (1999)</td>
<td>Position</td>
<td>Typing</td>
<td>-21.7</td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>Angular</td>
<td>Typing</td>
<td>24</td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>Angular</td>
<td>Typing</td>
<td>306</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

Note: "-" denotes extension in F/E plane and ulnar deviation in R/U plane

Marras and Schoenmarklin (1993) performed a quantitative surveillance study on the factory floor. Based on a total of 40 subjects from eight industrial plants, wrist deviation, angular velocity and acceleration variables were measured in three planes of wrist movements using dichotomous CTS risk levels (low and high risk). The results
indicate that angular velocity and acceleration appear to separate CTS risk levels more reliably than wrist position. The angular velocity and acceleration measures in high risk tasks showed increases of 46.2% and 67.1%, respectively, over these in low risk tasks. These results show the importance of dynamic components on assessing CTS risk.

Hansson et al. (1996) investigated the position and angular velocity variables for tasks in the fish processing industry as means for characterizing static and dynamic properties of wrist movements. The results indicated that wrist deviations in fish processing tasks are much smaller than these in the low risk tasks reported by Marras and Schoenmarklin (1993). However the angular velocities for F/E and R/U planes were 45% and 39%, respectively, higher than those of high risk tasks.

Marklin and Monroe (1998) measured wrist motions in bone trimming tasks using angular velocity and acceleration, and compared the results to those reported by Marras and Schoenmarklin (1993). Most bone trimming tasks for both left and right hands fell in the high risk category. Serina et al. (1999) conducted a laboratory study to continuously measure wrist and forearm postures and motions while typing. The results indicated that mean angular velocities and accelerations of typing task were similar to those of industrial tasks reported by Marras and Schoenmarklin (1993).

On the other hand, as a clinical application, Ojima et al. (1991) obtained preliminary data on the angular velocity - wrist angle loci of healthy men. The results showed that the loci of the healthy men were oval and the long axis of each locus was
inclined to the radiodorsal-ulnovolar direction from ordinate, while the loci of patients were smaller than those of the healthy men.

In conclusion, these studies demonstrated that dynamic components of wrist motions such as angular velocity and acceleration, are major contributing risk factors for CTS.

2.7.2 Biomechanical Models of Wrist Motions

Biomechanical models of the wrist motions may provide mechanisms for estimating the physical stress on the anatomical structures in the wrist joint under static and dynamic exertions, and may enhance our understanding of the kinematic aspects of the wrist joint.

2.7.2.1 Static Models

Landsmeer (1960, 1962) developed the most comprehensive set of biomechanical models for finger flexor tendon displacements, in which the tendon-joint displacement relationships are determined by the spatial relationships between the tendons and joints. In the first model, he assumed that 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. Landsmeer showed that the tendon and joint displacement relationship for such a joint is described by equation 2.1. However, if the tendon is not
held securely, it may be displaced away from the joint when the joint is flexed. Landsmeer considered this tendon configuration in his second model (see equation 2.2).

\[ x = R_1 \theta \]  
\[ x = 2R_2 \sin\left(\frac{\theta}{2}\right) \]  

(Equation 2.1)

(Equation 2.2)

where: \( x \) = tendon displacement past the joint

\( R_1 \) = distance from the joint center to the tendon (= tendon moment arm)

\( R_2 \) = distance from the joint center to the geometric tendon constraint

\( \theta \) = angle of joint rotation from neutral position

The biomechanical model for wrist joint proposed by Armstrong and Chaffin (1979b) is a static model that is based on Landsmeer's (1960, 1962) tendon model. Armstrong and Chaffin (1978) found when the wrist is flexed, the flexor tendons are supported by flexor retinaculum on the volar side of the carpal tunnel. When wrist is extended, the flexor tendons are supported by the carpal bones. Thus, deviation of the wrist from neutral position causes the tendons to be displaced against and past the adjacent walls of the carpal tunnel. Based on the mechanical principles of LeVeau (1977), they assumed that a tendon sliding over a curved surface is analogous to a belt wrapped around a pulley as shown in Figure 2.7.
Figure 2.7 Armstrong and Chaffin’s (1979b) model of a flexor tendon.

(Ft is the tendon force and Fr is the resultant reaction force exerted against the tendon)

The forces acting normal to tendon, tendon force and radius defined in equations as follow:

\[ F_L = \frac{F_t e^{\mu \theta}}{R} \]

where: \( F_L \) = supporting forces exerted on tendon

\( F_t \) = tendon force or belt tension

\( \mu \) = coefficient of friction between tendon and supporting tissues

\( \theta \) = wrist deviation angle (in radians)

\( R \) = radius of curvature around supporting tissues
Since the coefficient of friction ($\mu$) is considered small (0.0150) according to LeVeau (1977), it can be approximated by zero. Therefore, the equation is changed as following equation;

$$F_L = \frac{F_t}{R}$$

The above equation indicates that $F_L$ is a function of the tendon force and radius of curvature. As the tendon force increases or the radius of curvature decreases, the normal supporting force exerted on tendon increases.

The resultant reaction force, $F_R$, is the total supporting force of ligament and carpal bones, and depend on tendon force ($F_t$) and wrist deviation angle ($\theta$) as follow;

$$F_R = 2F_t \sin\left(\frac{\theta}{2}\right)$$

The above equation indicates that $F_R$ is independent of radius of curvature. As tendon force and wrist deviation angle increase, the resultant force increases linearly.

This model provides a relatively simple mechanism for calculating the normal supporting force exerted on tendon which are thought to be a major contributing factor in CTS. But this model does not include the dynamic components of wrist movements such as angular velocity and acceleration, which might be risk factors in work-related musculoskeletal disorders.
2.7.2.2 Dynamic Model

Schoenmarklin and Marras's (1990) dynamic biomechanical model extended Armstrong and Chaffin's (1979b) static model, includes dynamic component of angular acceleration. The dynamic model is two-dimensional in that only the forces in flexion and extension plane are analyzed. This model investigates the effects of maximum angular acceleration on the resultant reaction force that the wrist ligaments and carpal bones exert on tendons and their sheaths. The free body diagram (FBD) and mass×acceleration diagram (MAD) of the model are shown in Figure 2.8.

Figure 2.8 Schoenmarklin and Marras's (1990) biomechanical model.
The Figure 2.8 illustrates the reaction force on the center of the wrist ($W_x$ and $W_y$), the couple or moment ($M_w$) that required to flex and extend the wrist, inertial force ($M \times A_n$ and $M \times A_t$) and inertial moment ($I \times \dot{\Theta}$) acting around the hand's center of mass. In these relationships, the magnitude of moment around the wrist in FBD must equal the magnitude of moment acting around the hand's center of mass in MAD. Therefore,

$$F_i \times R = (M \times A_t + M \times A_n) \times D + I \times \ddot{\Theta}$$

Thus, the hand is assumed to accelerate from a stationary posture, so, the angular velocity is theoretically zero, resulted in zero centripetal force ($A_n = V^2/R = 0$). Then,

$$F_i \times R = (M \times A_t) \times D + I \times \ddot{\Theta}$$

$$F_i \times R = (M \times D \times \dot{\Theta}) \times D + I \times \dot{\Theta}$$

$$F_i = \frac{(M \times D^2 + I) \times \ddot{\Theta}}{R}$$

$$F_r = 2 \times \left( \frac{(M \times D^2 + I) \times \ddot{\Theta}}{R} \right) \times \sin \left( \frac{\theta}{2} \right) \quad \text{(from } F_r = 2F_i \sin \left( \frac{\theta}{2} \right) \text{)}$$

where: $R = \text{radius of curvature of the tendon}$

$D = \text{distance between the center of mass of hand and wrist}$

$M = \text{weight of hand}$

$I = \text{moment of inertia of the hand in flexion and extension}$

$\ddot{\Theta} = \text{angular acceleration}$

$\theta = \text{wrist deviation angle}$
The above equations indicate that the resultant reaction force, $F_R$, is a function of angular acceleration, radius of curvature and wrist deviation. Thus, exer-tions of the wrist and hand with large angular accelerations and deviated wrist angles would result in larger total resultant reaction forces on the tendons and supporting tissues than exertions with small angular accelerations and neutral wrist positions. According to Armstrong and Chaffin (1979b), increases in resultant reaction force would increase the supporting force that the carpal bones and ligaments exert on the flexor tendons, therefore increasing the chance of inflammation and risk of CTS. Therefore, these results might provide theoretical support to why dynamic variable such as angular acceleration can be considered a risk factor of CTS.

2.8 Pathophysiological Mechanism of CTS

Based on above-presented literature review and several previous models (Tanaka, and McGlothin, 1993; Hagberg et al., 1995; Katz, 1994; Moore et al., 1991; Werner and Armstrong, 1997), a conceptual pathophysiological mechanism as shown in Figure 2.9 is proposed to explain the cause of CTS.

Presentation of occupational risk factors such as forceful exertion, repetitive motions, and awkward postures may cause muscular fatigue and discomfort to the carpal tunnel at wrist. Several personal risk factors have been associated with diminished peripheral neurological function at carpal tunnel.
If sufficient recovery time is provided after manual works no matter what the tasks are static loads or dynamic loads, the fatigue and discomfort is short-lived. However if the workloads including forceful exertion, repetitive motions and awkward posture are continued despite fatigue and discomfort, the tendons become strained and lubrication of the tendons would become inadequate. The initial inflammation may progress to swelling of the structure within carpal tunnel (Sissons, 1979). This can happen, since the tendon sheaths appear to need a much longer time to restore their normal lubrication than the time needed for muscles to recover from their fatigues stage. This swelling causes a further increase in the carpal tunnel pressure.

If the pressure increase is sufficient, it causes local venous congestion within the vascular structure of the nerve, as well as ischemia in arerioles nourishing the nerve, leading to endoneurinal edema (Sunderland, 1976). The contribution of the ischemia to the nerve is supported by the relatively rapid development and recovery of acute CTS after the surgery of carpal tunnel release and precipitation of symptoms by pneumatic tourniquet test, in which blood flow to the nerve is restricted (Moore, 1992). The edema of the nerve segment increases the effect of the original compression, thus creating a vicious circle.

On the other hand, the mechanical pressure to the nerve causes the direct histologic change of the nerve including thinning or shearing of the myelin under the area of compression. Armstrong (1994) examined the structure in the carpal tunnel of cadaver
hands microscopically, and reported that the higher stresses were usually concentrated in the proximal regions than in the distal regions of the wrist.

Anyway, if this condition persists for a prolonged period of time, it leads to axonal deterioration of nerve that underlies the progressive long-term degenerative nature of median nerve mononeuropathy in carpal tunnel syndrome (Tanaka and MaGlothlin, 1993). Clinically, the patients feel numbness, tingling and pain in hand corresponding to distribution of the nerve. Various clinical tests including nerve conduction test across wrist reveal the abnormality.
Figure 2.9 Conceptional presentation of the pathophysiological mechanism of CTS
Chapter 3

LITERATURE REVIEW - NERVE CONDUCTION STUDIES

3.1 Clinical Diagnosis of CTS

3.1.1 Signs and Symptoms

Carpal tunnel syndrome (CTS) is the most commonly reported nerve entrapment syndrome at wrist due to localized compression to the median nerve in the carpal tunnel (Werner et al., 1997; AAEM et al., 1993a; Guidotti, 1992; Phalen, 1966, 1972). Early signs of the CTS include numbness or tingling in the fingertips, especially at night. As severity increases, one may experience constant aching, prickling, clumsiness, constant wrist pain, and restricted hand function (Morgan, 1991; Mosley, 1987).

3.1.2 Physical Examination and Tests

For early diagnosis of CTS, the patient's history and experience is the first and most important information. How the symptoms started, how it has progressed, and what works provoke symptomatic trauma (Putz-Anderson, 1990). This information may be obtained through either structured questionnaires or interviews with patients. Next step for detecting CTS is physical provocative test based on the assumption that irritation on the damaged median nerve facilitates the symptoms. Many tests have been developed to
provoke symptoms of carpal tunnel syndrome including; Phalen's Test, Tinel's Test, Reverse Phalen's Maneuver, Carpal Compression Test, Vibration Test, etc.

The most popular test has been the Phalen's Test (wrist flexion test), which involves unforced, complete hyperflexion of the wrist with fingers extensions for sixty seconds (Phalen, 1972; Gellman et al. 1986). A positive finding is numbness or paresthesia radiating into the median distribution of the hand.

A Reverse Phalen's Maneuver involves wrist and finger extension held for one minute. It has been demonstrated that wrist extension causes a larger increase in the intracarpal canal pressure when compared to wrist flexion (Robert et al., 1994). Pain, numbness or paresthesia radiating distally throughout the median distribution of the hand and wrist is a positive sign of CTS.

Another popular technique is the Tinel's Test, which consists of gentle percussion of the median nerve at the wrist. Paresthesia in the distribution of the median nerve indicate a positive response (Steward and Eisen, 1978).

Carpal Pressure Test consists of direct compression of the median nerve in the carpal tunnel for as long as thirty seconds (Durkan, 1994). Loss of vibration sensibility has been suggested as an early indicator of peripheral compression neuropathy including carpal tunnel syndrome. Clinical valuation of the peripheral sensibility of the hand with a tuning fork's vibratory stimuli is a valid, reliable, and quick test of functional integrity of the large myelinated nerve fibers (Dellon, 1980).
Each of the above provocative tests for evaluating carpal tunnel syndrome evokes a subjective response from the patient with varying sensitivity and specificity. Their sensitivity varies widely from 32% to 89% and the specificity 62% to 84% (Ghavanini and Haghighat, 1998). In their study, the Tinel's Test was the most specific (84%) and the least sensitive (32%) test, and vibration test was the most sensitive (89%) and the least specific (52%) test. As such, they should not be interpreted as unequivocal diagnoses, but rather as tools to assess the patient condition through symptomatic provocation.

3.2 Development of Nerve Conduction Evaluation Technique for CTS

Up to now, the most reliable and standard technique for assessing the severity of carpal tunnel syndrome is the nerve conduction studies (NCS), (Ghavanini and Haghighat, 1998; Katz. 1994), which is also called electrodiagnostic evaluation. Most patients should be referenced for nerve conduction studies if the diagnosis is suspected.

3.2.1 Development of Nerve Conduction Technique

Dawson and Scott (1949) reported the first reproducible recording of the nerve action potentials with surface electrodes in arms of health human subjects after electric stimulation of the nerves and suggested that the technique may be useful in detecting nerve damage. In 1956, Simpson reported the observation that the median motor distal latency was prolonged across the carpal tunnel in cases of CTS and this was confirmed by the other investigators; Thomas (1960) and Lanbert (1962).
Dawson (1956) reported a technique for measuring median sensory nerve conduction across the carpal tunnel, and Gilliat and Sears (1958) demonstrated slow median sensory nerve conduction across the carpal tunnel in patients with CTS. Buchthal and Rosenfalck (1971), Casey and LeQuesne (1972), and Brown et al. (1976) reported that the median nerve conduction abnormalities in CTS were focal and localized to the segment of the median nerve in the carpal tunnel.

3.2.2 Refinement of Nerve Conduction Technique

Over the past 45 years after Simpson's study, the techniques of median sensory and motor nerve conduction studies across the carpal tunnel have been refined to make the techniques more sensitive and specific for detection of compression of the median nerve in the carpal tunnel.

To make the nerve conduction studies more sensitive, investigators have developed techniques to exclude the normal segment of the median nerve, compared the speed of median nerve conduction to these of ulnar or radial nerve conduction from same hand, and performed sequential short segment (1cm) sensory and motor nerve conduction studies across the carpal tunnel. To improve the specificity of nerve conduction studies, researchers have used clinical criteria for diagnosis of CTS included concomitant evaluation of normal control subjects. The results of these clinical research efforts have found rapid application in the clinical laboratory, and have concluded that the nerve
conduction studies and electromyography (EMG) are of value for the laboratory
diagnosis of CTS (Katz et al., 1991; Jackson and Clifford, 1989; Stevens, 1987).

Nerve conduction studies for diagnosis of CTS can be performed in the laboratory
setting with surface stimulating and recording electrodes, and EMG for assessing CTS is
performed by inserting a sterile needle electrode through the skin into belly of a muscle
and evaluating the spontaneous and voluntary electric activity in the muscle. The two
techniques of nerve conduction studies and EMG are complementary but distinctly
different electrodiagnostic techniques, although they are often performed sequentially for
the evaluation of clinical problems.

3.3 Measurement of Nerve Conduction Parameters

3.3.1 Stimulation of the Nerve

One may use either surface or needle electrodes to stimulate the nerve. Stimulating electrodes consist of a cathode (negative pole) and an anode (positive pole). As the current flows between them, negative charges that accumulate under the cathode depolarize the nerve. Conversely, positive charges under anode hyperpolarize the nerve.

Most commercially available stimulators provide a probe that mounts the cathode and the anode at a fixed distance, usually 2 to 3 cm apart. The anode must be placed proximal to cathode while stimulating.

For nerve conduction studies, the nerve is stimulated at two or more points along
its course. The pulses of moderate intensity are used to adjust the positions of the cathode
until further relocation causes no change in the size of the muscle action potential. With the cathode at the best stimulating site, one then defines the maximal intensity that just elicits a maximal potential. Increasing the stimulus further should result in no change in the size of the muscle potential. The use of 20 to 30 percent supramaximal intensity guarantees the activation of all the nerve axons innervating the recorded muscle.

Surface stimulation of 0.1 msec duration, and 100 to 300 V or 5 to 40 mA intensity usually activates a health nerve fully, and the output of impulse provides a square wave of variable duration. Electrical stimulation within the above intensity range causes no particular risk to an ordinary patient. Special care to safeguard the patient includes proper grounding and placement of the stimulator with sufficient distance from the pacemaker (AAEE, 1984).

Stimulation by a needle electrode inserted subcutaneously close to the nerve requires much less current than surface stimulation to elicit the same response. The anode may be a surface electrode located on the skin nearby or a second needle electrode inserted in the vicinity of cathode.

3.3.2 Recording of Motor and Sensory Nerve Action Potentials

Recording action potentials of motor and sensory requires a pair of surface electrodes or needle electrodes; a cathode (-) and an anode (+). With this arrangement, the propagating action potential, originating under cathode, give rise to a simple biphase waveform with initial negativity.
Surface electrodes, in general, are better than needle electrodes for recording compound motor nerve action potentials in assessing contributions from all discharging units, because its onset latency indicates the conduction time of the fastest fibers, whereas its amplitude is approximately proportional to the number of available axons. The use of a needle electrode improves the recording from small atrophic muscles because the needle electrode registers only a small portion of the muscle action potential with less interference from neighboring discharges.

Motor studies are usually performed with filter set at 2 Hz to 10 kHz. Measuring parameters of motor nerve action potentials include onset latency (msec), amplitude (mV) and duration (msec).

Routine recording of the sensory nerve action potential, in general is performed with surface ring electrodes which provide adequate and reproducible information noninvasively. (Burnham and Steadward, 1994; Jackson and Clifford, 1989; Kimura, 2001; Tashjian et al., 1987). Some electromyographers, however, prefer needle electrodes placed perpendicular to the nerve to improve the resolution, and to improve the signal-to-noise ratio (Rosenfalck, 1978).

Sensory studies are usually performed with filters set at 20 Hz to 2 kHz. Measuring parameters of sensory nerve action potentials include amplitude (µV), duration (msec), and onset and peak latency (msec). Usually, the peak latency is preferred to onset latency because it better reflects nerve fiber compromise. Health nerve fibers in a partially compromised nerve could maintain stable onset latency but the delayed
conduction through the compromised fibers prolongs the peak latency (Johnson and Terebuh, 1997).

3.3.3 Antidromic and Orthodromic Techniques

The terms antidromic (AD) and orthodromic (OD) techniques are used relative to the physiologic direction of propagation of an action potential in a given nerve fiber. In sensory nerve fiber, for example, if an action potential is stimulated at a distal point and recorded proximal to the point of stimulation, that is an orthodromic (OD) nerve conduction technique. If the process is reversed by stimulating the sensory nerve fibers proximal to the recording points, then the technique is an antidromic (AD) nerve conduction, which is also called as distal nerve conduction.

The major advantage of an orthodromic (OD) technique is that only sensory fibers are stimulated and recorded. It has also been suggested that orthodromic (OD) nerve conduction parameters are less affected by change of temperature (Chodoroff et al., 1985). The primary advantage of the antidromic (AD) technique is greater amplitude of nerve action potentials compared to orthodromic (OD) technique because the digital nerves lie nearer to the surface. The amplitude of sensory nerve action potential is essential to establish the severity of CTS and its progress. MacDonnel et al. (1990) reported the antidromic (AD) technique is the more sensitive method for assessing mild carpal tunnel syndrome.
3.3.4 Common Electrode Placements for Antidromic Technique

The conventional site of stimulation for sensory nerve conduction studies is wrist. At the wrist, the cathode might be placed 3cm proximal crease of the wrist (Kimura, 2001). Alternative techniques use a fixed distance from the recording electrode, most commonly 12 to 14 cm (DiBenedetto et al., 1986; Jackson and Clifford, 1989; Carroll, 1987). Sensory potentials can be recorded from the first, second, third digit or lateral half of the fourth digit, commonly second or third digit in which surface ring electrodes usually placed around the proximal (cathode) and distal interphalangeal joints (anode), or fixed distance of 4 cm between cathode and anode (Dumitru et al., 1988). Table 3.1 describes the common sites of electrode placement for each nerve including median, ulnar, and radial nerve. Figure 3.1(a) and Figure 3.1(b) present the pictures of stimulating and recording sites for median motor and sensory nerve conduction studies, respectively.
Table 3.1 Common electrode placement for each nerve and fibers

<table>
<thead>
<tr>
<th>Nerve</th>
<th>Fibers</th>
<th>Stimulation Site</th>
<th>Distance</th>
<th>Recording Site</th>
<th>Ground Site</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cathode</td>
<td>Anode</td>
<td>Cathode</td>
<td>Anode</td>
</tr>
<tr>
<td>Median Motor</td>
<td>Fixed distance from recording electrode mostly 7 to 8 cm, or 3 cm proximal to the distal crease at wrist</td>
<td>2 to 3 cm proximal to cathode</td>
<td>7~8 cm</td>
<td>The belly of the Abductor Pollicis Brevis (APB) at thumb</td>
<td>The tendon of Abductor Pollicis Brevis (APB) at thumb</td>
</tr>
<tr>
<td>Sensory</td>
<td>Fixed distance from recording electrode mostly 12 to 14 cm, or 3 cm proximal to the distal crease at wrist</td>
<td>2 to 3 cm proximal to cathode</td>
<td>12~14 cm</td>
<td>Proximal interphalangeal joints (PIP) of second or third digits</td>
<td>Distal interphalangeal (DIP) joints or 4 cm distal to cathode</td>
</tr>
<tr>
<td>Ulnar Motor</td>
<td>Fixed distance from recording electrode mostly 7 to 8 cm, or 3 cm proximal to the distal crease at wrist</td>
<td>2 cm proximal to cathode</td>
<td>7~8 cm</td>
<td>Belly of the abductor digitii minimi (ADM)</td>
<td>Tendon of the abductor digitii minimi (ADM), 3cm distally</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fixed distance from recording electrode mostly 12 to 14 cm, or 3 cm proximal to the distal crease at wrist</td>
<td>2 to 3 cm proximal to cathode</td>
<td>12~14 cm</td>
<td>Proximal interphalangeal (PIP) joints of the fifth or fourth digits</td>
</tr>
<tr>
<td>Radial Motor</td>
<td>Forearm at lateral edge of the extensor carpi ulnaris (ECU) muscle 8 to 10 cm proximal to the styloid process</td>
<td>2 cm proximal to cathode</td>
<td>7~8 cm</td>
<td>Monopolar needle electrode in the extensor indicis</td>
<td>Dorsum of hand laterally</td>
</tr>
<tr>
<td>Sensory</td>
<td>Lateral edge of the radius in the distal forearm</td>
<td>2 to 3 cm proximal to cathode</td>
<td>7~8 cm</td>
<td>Metacarpal phalangeal (MP) joint of first digit</td>
<td>Intercarpal (IP) joint of first digit</td>
</tr>
</tbody>
</table>
Figure 3.1 Stimulating and recording electrodes placements for antidromic technique
(source: Jabre and Hackett, 1983)
3.3.5 Nerve Conduction Measures

Nerve conduction parameters include latency, amplitude, and conduction velocity. Followings are the explanations of its terms including units. An example waveform is presented in Figure 3.2.

![Figure 3.2 Normal median nerve waveform](image_url)

- Onset latency (msec): time between nerve stimulation and initial response detected at the active recording electrode (SO).
- Peak latency (msec): time between nerve stimulation and peak response detected at the active recording electrode (SP).
- Amplitude (mV for motor NCS; µV for sensory NCS): height of the waveform between onset and negative peak (OP) or negative peak and positive peak (PT).
- Conduction velocity (ms⁻¹): calculated by dividing stimulated nerve length by onset latency (Length/SO) for sensory nerve.
3.3.6 Motor and Sensory Nerve Conduction Velocity

For motor nerve conduction studies, latency consists of two components; (1) nerve conduction time from the stimulus point to the nerve terminal, and (2) neuromuscular transmission time from the axonal terminal to the motor end plate, including the time required for generation of muscle action potentials. Onset latency is a measure of the fastest conducting motor fibers (Kimura, 2001).

To calculate the pure motor nerve conduction velocity, one must eliminate the time for neuromuscular transmission and generation of muscle action potentials. Latency difference between the two responses elicited by stimulation of two separate points, in effect, excludes the two components common to both stimuli. Thus, it represents the time necessary for the nerve impulse to travel between the two stimulus points. The motor nerve conduction velocity (MNCV) is derived as the ratio between the distance from one point of stimulation (Site A) to the next (Site B) and the corresponding latency difference between them.

\[
\text{MNCV}(\text{m/sec}) = \frac{\text{Distance between site.A and site.B (mm)}}{(\text{Latency of site.A} - \text{Latency of site.B})(\text{msec})}
\]

The reliability of results depends on accuracy in determining the length of the nerve segment, estimated with the surface distance along the course of the nerve.

Unlike motor latency, which includes neuromuscular transmission, sensory latency consists only of the nerve conduction time from the stimulus point to the
recording electrode. Therefore, stimulation of the nerve at a single site is enough for calculation of sensory nerve conduction velocity, which is calculated by dividing stimulated nerve length by onset latency.

3.4 Normal Values of Motor and Sensory Conduction Studies

3.4.1 Median Motor Nerve Conduction Studies

The recording of median motor latency to the abductor pollicis brevis (APB) muscle after stimulating the median nerve in the wrist has been a standard method for assessing carpal tunnel syndrome (Johnson et al., 1962). Median motor nerve latency has been shown to be prolonged in 54% to 83% of cases in studies of patients with CTS, and the median motor nerve amplitude in cases of CTS has been shown to be decreased compared with normal subjects (Kimura, 2001; Kimura, 1979; Thomas, 1960; Simpson, 1956). Some authors have ever shown a reduced median forearm motor nerve conduction velocity by 10% to 22.6% in the presence of CTS (Kimura, 1979; Kimura and Ayyar, 1985; Thomas, 1960). Table 3.2 presents normal median motor nerve conduction values.
Table 3.2 Normal values for median motor nerve conduction

<table>
<thead>
<tr>
<th>Authors</th>
<th>Onset Latency (msec)</th>
<th>Amplitude (mV)</th>
<th>Conduction Velocity (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Abnormal (&gt;2SD)</td>
<td>Normal</td>
</tr>
<tr>
<td>Burnham &amp; Steadward (1994)</td>
<td>3.63±0.28</td>
<td>4.2</td>
<td>12.8±4.0</td>
</tr>
<tr>
<td>Jackson &amp; Clifford (1989)</td>
<td>3.2±0.27</td>
<td>3.8</td>
<td>12.6±3.22</td>
</tr>
<tr>
<td>Kimura (2001)</td>
<td>3.49±0.34</td>
<td>4.2</td>
<td>n.a.</td>
</tr>
<tr>
<td>Kimura (1979)</td>
<td>3.6±0.36</td>
<td>4.3</td>
<td>n.a.</td>
</tr>
<tr>
<td>Melvin et al. (1973)</td>
<td>3.7±0.3</td>
<td>4.5</td>
<td>13.2±5.0</td>
</tr>
<tr>
<td>Thomas et al. (1967)</td>
<td>3.4±0.48</td>
<td>4.4</td>
<td>n.a.</td>
</tr>
<tr>
<td>Johnson &amp; Olsen (1960)</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>3.5</td>
<td>4.2</td>
<td>12.9</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>3.2~3.7</td>
<td>3.8~4.5</td>
<td>12.6~13.2</td>
</tr>
</tbody>
</table>

Note: All data are antidromic

The distal onset latency usually ranges between 3.2 and 3.7 msec, and motor nerve amplitude ranges between 12.6 and 13.2 mV, and the conduction velocity range between 48.8 and 59.6 m/sec. The upper or lower limits for assessing CTS (usually, mean±2SD) range between 3.8 to 4.5 msec for latency, 3.0 to 6.1 mV for amplitude and 32.4 to 52.0 m/sec for conduction velocity. However, it is important to note that most of these investigators measured distal median motor nerve conduction parameters over various experimental settings, different room and skin temperatures and conduction distances instead of over a standard setting.
3.4.2 Median Sensory Nerve Conduction Studies

Table 3.3 presents the results of median sensory nerve conduction studies with stimulation of wrist and record site of digit. These studies determined that between 49% and 66% of patients with CTS demonstrate either a prolonged median sensory peak latency or the median sensory nerve action potential was absent with conduction between the wrist and a digit. Other median sensory nerve conduction studies of onset latency, peak latency and conduction velocity with conduction between the wrist and a digit reported 64% to 92% incidence of abnormal finding in patients with CTS (Stevens, 1987; Felsenthal and Spindler, 1979; Kimura and Ayyar, 1985; Kemble, 1968). Most authors used the index finger for stimulation or recording, but some used the middle finger.

Table 3.3 Normal values for median sensory nerve conduction

<table>
<thead>
<tr>
<th>Authors</th>
<th>Onset Latency (msec)</th>
<th>Peak Latency (msec)</th>
<th>Amplitude (µV)</th>
<th>Conduction Velocity (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Abnormal (&gt;2SD)</td>
<td>Normal</td>
<td>Abnormal (&gt;2SD)</td>
</tr>
<tr>
<td>Burnham &amp; Steadward (1994)</td>
<td></td>
<td></td>
<td>44.9±14.8</td>
<td>15.1</td>
</tr>
<tr>
<td>Jackson &amp; Clifford (1989)</td>
<td>2.47±0.12</td>
<td>2.7</td>
<td>3.16±0.16</td>
<td>3.5</td>
</tr>
<tr>
<td>Kimura (2001)</td>
<td>2.87±0.31</td>
<td>3.5</td>
<td>38.4±15.6</td>
<td>19</td>
</tr>
<tr>
<td>Kimura (1979)</td>
<td>2.82±0.28</td>
<td>3.4</td>
<td>41.3±19.3</td>
<td>2.5</td>
</tr>
<tr>
<td>Melvin et al. (1973)</td>
<td>3.2±0.2</td>
<td>3.8</td>
<td>41.6±25.0</td>
<td>0</td>
</tr>
<tr>
<td>Johnson &amp; Melvin (1967)</td>
<td>3.0±0.4</td>
<td>4.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>2.5–2.8</td>
<td>2.7–3.5</td>
<td>3.0–3.2</td>
<td>3.5–4.0</td>
</tr>
</tbody>
</table>

Note: All data are antidromic
In Table 3.3, the distal onset latency usually ranges between 2.5 and 2.8 msec, and peak latency ranges between 3.0 and 3.2 msec, and motor nerve amplitude ranges between 32.9 and 44.9 µV, and the conduction velocity ranges between 56.2 and 58.3 m/sec. The upper or lower limits for assessing CTS (usually, mean±2SD) have range between 2.7 to 3.5 msec for onset latency, 3.5 to 4.0 msec for peak latency, 0 to 19 µV for amplitude and 44.4 to 48.7 m/sec for conduction velocity. From these data, it appears that onset and peak latencies, and conduction velocity have the narrow range of normal values, and the amplitude have rather wide normal ranges.

3.4.3 Ulnar and Radial Sensory Nerve Conduction

A nerve-to-nerve comparison of the median nerve with the radial or ulnar nerves in same hand is essential to a comprehensive CTS evaluation. This process could clarify the confounding effects of a generalized peripheral neuropathy as well as increase the sensitivity of diagnosis CTS. Felsenthal and Spindler (1979) performed a 14 cm antidromic sensory nerve action potential technique to index finger and little finger for comparison of median and ulnar nerve. They concluded that a difference greater than 0.46 msec between median and ulnar sensory nerve peak latencies in the same hand was suggestive of CTS.

Johnson et al. (1981) established normal values for the median and ulnar nerve sensory nerve action potential parameters in little finger using a 14 cm antidromic technique. They reported that a peak latency disparity of greater than 0.3 msec is
suggestive of CTS because 93% of all normal hands demonstrated a median to ulnar peak latency difference of 0.3 msec or less. In similar study, Jackson and Clifford (1989) reported $0.09 \pm 0.13\text{msae}$ difference of median and ulnar peak latency, and demonstrated peak disparity of 0.35 msec is suggestive of CTS with 82% symptomatic hands of abnormal studies.

Johnson et al. (1987) established a comparison study of median to radial sensory nerve in thumb with a 10-cm antidromic sensory nerve action potential technique. They concluded that a peak latency disparity of greater than 0.4 msec between median and radial is suggestive of CTS because 93% of normal subjects demonstrated a difference of 0.4 msec or less. Carroll (1987) and Jackson and Clifford (1989) determined the difference between the median and radial nerve latency measurements, and reported that less than 0.3–0.4 msec difference was normal with 66% (Carroll, 1987) and 69% (Jackson and Clifford, 1989) percentage symptomatic hands of abnormal studies. Normal ulnar and radial sensory conduction values to be compared with median nerve are summarized in Table 3.4.
### Table 3.4 Normal values for ulnar and radial sensory nerve conduction

<table>
<thead>
<tr>
<th>Nerve</th>
<th>Authors</th>
<th>Latency (msec)</th>
<th>Amplitude (µV)</th>
<th>Conduction Velocity (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Normal Abnormal (&gt;2SD)</td>
<td>Normal Abnormal (&lt;2SD)</td>
<td>Normal Abnormal (&lt;2SD)</td>
</tr>
<tr>
<td>Ulnar Nerve</td>
<td>Burnham &amp; Steadward (1994)</td>
<td>26.7±9.8 (Digit 4) 42.7±18.0 (Digit 5)</td>
<td>7.1 6.7</td>
<td>55.7±4.7 (Digit 4) 58.1±5.7 (Digit 5)</td>
</tr>
<tr>
<td></td>
<td>Kimura (2001)</td>
<td>2.54±0.29 (Digit5)</td>
<td>3.12</td>
<td>35.0±14.7 (Digit5)</td>
</tr>
<tr>
<td>Radial Nerve</td>
<td>Burnham &amp; Steadward (1994)</td>
<td></td>
<td></td>
<td>59.4±5.6 (Digit1)</td>
</tr>
<tr>
<td></td>
<td>Kimura (2001)</td>
<td>2.37±0.22 (Digit1)</td>
<td>2.81</td>
<td>13±7.5 (Digit1)</td>
</tr>
</tbody>
</table>

Kimura (2001) reported that the normal value of the ulnar sensory nerve latency was 2.54±0.29 msec and that of radial latency was 2.37±0.22 msec. Burnham and Steadward (1994) established the normal conduction velocities of the ulnar and radial sensory nerve were 58.1±5.7 for ulnar nerve of little finger, 59.4±5.6 for radial nerve for thumb. From these data of ulnar nerve, it appears that the amplitude and conduction velocity of little finger are slightly larger or faster than these of ring finger.

### 3.5 Factors affecting Nerve Conduction Parameters

Independent of pathology to peripheral nerves, there are several other factors that influence nerve conduction parameters. Therefore, it is necessary to consider these factors to avoid false-positive CTS diagnosis based on erroneous interpretation of nerve conduction measurement.
3.5.1 Skin Temperature

Temperature has a profound effect on nerve conduction parameters (Letz and Gerr, 1994; Baysal et al., 1993). As the skin temperature decreases, the nerve conduction action potential recorded from a nerve demonstrates an increased amplitude and prolonged latency. The physiological mechanism between temperature change and nerve conduction measures was reported by several researchers (Rutkove, 2001; Burke et al., 1999a; Burke et al., 1999b, Rutkove et al., 1997). The permeability of the cell membrane to various ions and the concentrations of those ions inside and outside the cell produce a net potential difference across the membrane. K⁺ (Potassium) is sequestered within the cell while Na⁺ (Sodium) is pumped out, resulting in a resting membrane potential of approximately -60mV for neurons. Temperature appears to have only a modest effect on neuronal resting membrane potential. The depolarization of a single nerve axon is due to the abrupt inward flux of Na⁺ ions. This influx of Na⁺ ions may occur due to the opening of voltage-gated channels along the axon or to the binding of a neurotransmitter as occurs on the muscle endplate. At low temperature, both the opening and closing of the Na⁺ channels slow down, with the closing being more affected than the opening. Thus the Na⁺ channels remain open for longer period of time, increasing the ion flux and a larger depolarization. This phenomenon translates into a prolonged latency, a longer duration, and increased amplitude response.
Reversely, nerve impulses conduct faster at higher body temperature. The conduction velocity increases almost linearly, by 2.4 m/sec per degree as the temperature measured near the nerve increases form 29 to 38°C (Johnson and Olson, 1960). Also, Lee et al. (1993) reported that the antidromic median sensory nerve latency was delayed by 0.1 msec/degree with cooling, and Tashjian et al. (1987) reported that the median sensory nerve amplitude was found to increase with upper extremity cooling with the antidromic technique by 3.5µV per degree.

However, correction factors for skin temperature are typically only employed when wrist temperature is beyond normal ranges, defined as 29.6 ~ 33.4°C (Halar et al, 1983). To improve the sensitivity of nerve conduction studies, Jackson and Clifford (1989) suggest guidelines that are more stringent, where skin temperature measured at the wrist midline is defined to be normal only when greater than 31.0°C.

3.5.2 Age

Slowing of median nerve function occurs naturally with increasing age though not necessarily leading to the development of CTS (Nathan et al., 1988, 1992). Specifically, median sensory nerve conduction velocity was found to decrease by 1.3 m/sec per ten-year increase in age (Stetson et al., 1992; Letz and Gerr., 1994). In other study, Chodoroff et al. (1985) reported that the sensory nerve conduction velocity has been shown to decline by 1 m/sec per decade.
3.5.3 Gender

Normal median nerve conduction parameters are found to be undifferentiated between male and female populations after correcting other variables (Nathan et al., 1988, 1992; Stetson et al., 1992; Robinson et al., 1993).

3.5.4 Body Mass Index (BMI)

Effects of Body Mass Index (BMI) on median nerve conduction are conflicting. Nathan et al. (1992) reported a strong positive correlation, while Letz and Gerr (1994) reported a small negative association between measures.

3.6 Standards for Measuring Nerve Conduction Parameter

There is no gold standard setting for measuring nerve conduction parameter. Each investigator uses his own laboratory setting for evaluating CTS with their own normal nerve conduction values for control populations. But we can make a consensus experimental setting for stimulating and recording site, and distance between them, and skin temperature, and etc., based on previous studies including literature review of AAEM (1993b). Table 3.5 shows the standard method for measuring nerve conduction parameters.
Table 3.5 Standards for measuring nerve conduction parameters

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Median sensory nerve</th>
<th>Median motor nerve</th>
<th>Ulnar sensory nerve for comparison with median sensory nerve</th>
<th>Radial sensory nerve for comparison with median sensory nerve</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stimulation Site</strong></td>
<td>Cathode</td>
<td>Proximal to distal cease at wrist</td>
<td>Proximal to distal cease at wrist</td>
<td>Proximal to distal cease at wrist</td>
</tr>
<tr>
<td></td>
<td>Anode</td>
<td>2 cm proximal to cathode for anode</td>
<td>2 cm proximal to cathode for anode</td>
<td>2 cm proximal to cathode for anode</td>
</tr>
<tr>
<td><strong>Recording Site</strong></td>
<td>Cathode</td>
<td>Proximal interphangeal at index finer</td>
<td>The belly of the Abductor Pollicis Brevis (APB) at thumb</td>
<td>Proximal interphangeal at little finer</td>
</tr>
<tr>
<td></td>
<td>Anode</td>
<td>4 cm distal to cathode</td>
<td>The tendon of the Abductor Pollicis Brevis (APB) at thumb</td>
<td>4 cm distal to cathode</td>
</tr>
<tr>
<td><strong>Grounding electrode</strong></td>
<td></td>
<td></td>
<td>Palm between metacarpal phalanges of meddle and ring fingers</td>
<td>Palm between metacarpal phalanges of meddle and ring fingers</td>
</tr>
<tr>
<td><strong>Distance between stimulation and recording</strong></td>
<td>14 cm</td>
<td>7 cm</td>
<td>14 cm</td>
<td>10 cm</td>
</tr>
<tr>
<td><strong>Minimum skin temperature of hand</strong></td>
<td>31 °C</td>
<td>31 °C</td>
<td>31 °C</td>
<td>31 °C</td>
</tr>
<tr>
<td><strong>Criteria for abnormal value</strong></td>
<td>Mean ± 2SD</td>
<td>Mean ± 2SD</td>
<td>Mean difference ± 2SD</td>
<td>Mean difference ± 2SD</td>
</tr>
</tbody>
</table>
Chapter 4
MEASUREMENT SYSTEM

4.1 Force Measurement

Methods of measuring force can vary depending on the task situation and practical considerations such as the required accuracy and the equipment available. Simple mechanical devices such as a dynamometer can be used to estimate lift/pull/push forces in many instances. However this device does not represent various handgrips well and it is impossible to measure segmental forces or even individual finger forces. Another method of measuring force involves placing electronic load cells at the points of contact of the force. To measure hand or finger forces, small pressure-sensitive devices are attached to the hand or fixture while the individual performs a task. Currently available electronic load cells are strain gauge, the piezoelectric force sensor, and the conductive polymer force sensor (Jensen et al., 1991).

Most commercial force measurement transducers using strain gauges are either too large and bulky for attaching to hand held fixture, or too fragile to withstand the high forces exerted by the hand. A cylinder instrumented with strain gauged pads has been used to analyze of the forces exerted by an individual finger and the forces exerted by the individual finger phalangeal segments (An et al. 1986; Radhakrishnan and Hagaravindra,
1993). Rapidly changing forces can be measured using piezoelectric force sensors. Although these sensors operated with high resolution, high repeatability and low hysteresis, they are highly fragile and very brittle.

A variety of thin, durable and flexible conductive polymer sensors have been found useful for measuring external forces when conventional force sensors are too large. These include Force Sensing Resistor (Interlink Electronics, CA), UniForce sensor (Force Imaging Technologies, IL) and FlexiForce (A101 resistance sensors, Tekscan, Inc., MA). Since several practical uses for these sensors have been demonstrated, these sensors are useful for numerous applications in ergonomics and biomechanics (Fellow and Freivalds, 1991; Yun and Freivalds, 1995; Park, 1999).

FlexiForce resistance sensors (A101, Tekscan, Inc., MA) were used in this study. The FlexiForce resistance sensor is a type of conductive polymer sensor. The FlexiForce sensors are chosen primary because of its durability and good linearity.

4.1.1 Structure of Force Sensor

With its paper-thin construction, flexibility and force measurement ability, the FlexiForce™ sensor can measure force between almost any two surfaces and is durable enough to stand up to most environments. The FlexiForce™ A101 sensor is an ultra-thin (0.005"), flexible printed circuit. It is 14 mm (0.55") wide and 203 mm (8") in length. The active sensing area is a 95 mm (0.375") diameter circle at the end of the sensor. The
range of forces applicable to the sensor is 0 N to 110 N (25 lb.). Figure 4.1 shows a picture of the FlexiForce sensor.

![FlexiForce sensor](image)

**Figure 4.1** A FlexiForce sensor

The sensors are constructed of two layers of substrate, such as a polyester film. On each layer, a conductive material is applied, followed by a layer of pressure-sensitive ink. Adhesive is then used to laminate the two layers of substrate together to form the sensor. The active sensing area is defined by the silver circle on top of the pressure sensitive ink. Silver extends from the sensing area to the connectors at the other end of the sensor, forming the conductive leads. A101 sensors are terminated with a 3-pin Berg
Clincher™ connector, which allows them to be incorporated into a circuit. The two outer pins of the connector are active and the center pin is inactive.

The FlexiForce™ single element sensor acts as a resistor in an electrical circuit. When the sensor is unloaded, its resistance is very high. When a force is applied to the sensor, this resistance decreases. The resistance can be read by connecting an ohmmeter to the outer two pins of the sensor connector and applying a force to the sensing area.

### 4.1.2 Calibration of Force Sensor

An experiment was conducted to test the general characteristics of the force sensor such as non-repeatability and non-linearity on a custom-made balancing calibration device, which was developed by Park (1999). Three different sensors of FlexiForce A101 were randomly chosen, and seven known masses (0.82, 5.72, 11.27, 22.54, 42.14, 61.74, 81.34 N) were placed on the sensors. The choice of seven masses came from the recommendation of Laurie and Andres's (1992) study. In this study, drops of epoxy were added on the sensor's sensing area for allowing even distribution of load based on studies of Jensen et al. (1991) and Park (1999). Once good contact was established between the mass and the sensor surface, sampling began. Data were sampled at 248 Hz for 3 seconds using the FlexComp system (Thought Technology Ltd., NY) and its DSP board in a desktop PC (Gateway2000, Pentium PS-100). A 65 msec moving average smoothing filter was applied to further condition the digitized signal.
After sampling, the next mass was placed in the device so as not to disturb the load distributor placement. This procedure was followed until all masses were tested on one sensor. Each measurement condition was randomized and 3 trials for each sensor were obtained.

Analysis of variance (ANOVA) on force sensor measurements was conducted for force, sensor, day and trial variables, and the results are shown in Table 4.1. The force sensor measurements significantly varied for force changes (P<0.001, F=6413.46) and sensors (P<0.001, F=217.84), but were consistent across day (P>0.05, F=1.31) and trial (P>0.05, F=0.55). Figure 4.2 showed that the true force values and measurements values have strong relationships across all the range of forces (p<0.001, R^2=99.8% for Sensor A). Regression model for the sensor A were developed to predict true force values based on measurement values, and presented in the figure.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>FORCE</td>
<td>6</td>
<td>79400767</td>
<td>13233461</td>
<td>6413.46</td>
<td>0.000</td>
</tr>
<tr>
<td>SENSOR</td>
<td>2</td>
<td>898992</td>
<td>449496</td>
<td>217.84</td>
<td>0.000</td>
</tr>
<tr>
<td>DAY</td>
<td>3</td>
<td>8089</td>
<td>2696</td>
<td>1.31</td>
<td>0.272</td>
</tr>
<tr>
<td>TRIAL</td>
<td>2</td>
<td>2279</td>
<td>1140</td>
<td>0.55</td>
<td>0.576</td>
</tr>
<tr>
<td>Error</td>
<td>490</td>
<td>1011060</td>
<td>2063</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>503</td>
<td>81321186</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Further analysis for non-repeatability and non-linearity were conducted as shown in Table 4.2 and the results indicated that non-repeatability for sensor A was 17.5% for between day, and 14.3% for within day, and the non-linearity were 1.6% for the sensor. The hysteresis appeared in these examination was 3.3%.

In summary, the present evaluation of force sensors demonstrated that the sensor output has strong relationship with true force for all range of forces, and the sensor output has stable non-linearity of 1.6%. Also, since the results demonstrated that the sensor
measurements were consistent across day and trial, it is not necessary to calibrate the measures for each day reducing setup time.

Table 4.2 Non-repeatability and non-linearity for force sensor A

<table>
<thead>
<tr>
<th>Force (N)</th>
<th>Non-repeatability</th>
<th>Non-linearity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Between Day</td>
<td>Within Day</td>
</tr>
<tr>
<td>0.82</td>
<td>41.8%</td>
<td>36.1%</td>
</tr>
<tr>
<td>5.72</td>
<td>26.4%</td>
<td>18.4%</td>
</tr>
<tr>
<td>11.27</td>
<td>15.8%</td>
<td>12.0%</td>
</tr>
<tr>
<td>22.54</td>
<td>13.6%</td>
<td>12.0%</td>
</tr>
<tr>
<td>42.14</td>
<td>12.5%</td>
<td>11.4%</td>
</tr>
<tr>
<td>61.74</td>
<td>9.1%</td>
<td>6.2%</td>
</tr>
<tr>
<td>81.34</td>
<td>3.3%</td>
<td>3.6%</td>
</tr>
<tr>
<td>AVG</td>
<td>17.5%</td>
<td>14.3%</td>
</tr>
</tbody>
</table>

Note: Non-repeatability is defined by the maximum output minus the minimum output divided by the maximum output. Non-linearity is defined by the maximum input deviation divided by the full-scale input.

4.2 Hand Posture Measurement

Several devices have been proposed for measuring wrist joint motions under static or dynamic conditions, but none has received universal acceptance. One such approach is based on videotape analysis of wrist motion. Developed by Armstrong et al. (1982), it utilizes a frame-by-frame analysis of videotape that records wrist flexion/extension in one of five categories and radial/ulnar deviation in one of three categories. This method requires considerable time and effort because each individual frame has to be analyzed manually, and yields absolute resolutions of only 30° for flexion/extension and 20° for
radial/ulnar deviation. In addition, dynamic variables of the wrist, such as angular velocity and acceleration, are not easily obtainable with this type of analysis.

Another such method of wrist motion measurement was developed by Logan and Groszewski (1989) and utilizes an electromagnetic three space-digitizer sensor system to obtain real-time six degrees of freedom position information. Sensors determine specific x, y, z coordinates and θ, φ, ψ orientation angles with respects to a coordinate system based on a low-frequency magnetic field. Further analysis of this data provides flexion/extension, radial/ulnar deviation, and pronation/supination angles. Although this system provided useful information for a number of work tasks in food processing industry, the system appeared to require excessive amount of time for data acquisition and reduction and had limitations due to its instrumentation and magnetic noise.

One electromechanical goniometer was developed by Marras and Schoenmarklin (1991) to collect on-line data of wrist movements of flexion/extension, radial/ulnar deviation, and pronation/supination planes simultaneously. Further analyses of the data yielded angular velocity and acceleration. This wrist monitor was composed of two thin metal strips, placed on two adjacent segments with a rotary potentiometer placed at the center of the joint. This system produced relatively accurate and repeatable results, however it was uncomfortable and obtrusive for subject to move freely in the normal environment. Furthermore, being custom built, this wrist monitor is not generally available.
A very common approach is the simple electrogoniometer with its output assessed electrically. Typically, the electrogoniometers are relatively small and lightweight offering quick and objective measurements of wrist joint motions (Nicole 1987; Ojima et al., 1991; Hansson et al., 1996; Buchholz and Wellman, 1997). Numerous studies have already been performed using the electrogoniometers in laboratory, factory, and clinical fields. For example, Smutz et al. (1994) employed an electrogoniometer for measuring wrist posture in their ergonomic assessment of keyboard design. Moore et al. (1991) used the electrogoniometer to quantify wrist motions of ergonomic risk factors, and Ojima et al. (1991) performed a dynamic analysis of wrist circumduction using the electrogoniometer in clinical field.

There are several commercial electrogoniometers (Biometrics Ltd., Gwent, UK, and BIOPAC Systems Inc, Santa Barbara, CA, USA) currently available for measuring both wrist flexion/extension and radial/ulnar deviation, and forearm rotation of pronation/supination. In this study, a flexible biaxial electrogoniometer (XM110, Biometrics, Gwent, Uk) was used.

4.2.1 Structure of Electrogoniometer

The biaxial electrogoniometer consist of two plastic end blocks which are separated by a flexible spring protecting a strain wire. The goniometers incorporate gauge elements which measure bending strain along or around a particular axis. The biaxial
goniometers measure orthogonal rotational axes simultaneously (e.g. wrist flexion/extension and radial/ulnar deviations). It is 18 mm (0.7") wide and 65 mm (2.6") in length. The measuring range of angles is +150 degrees. Figure 4.3 shows a picture of the electrogoniometer sensor.

Figure 4.3 Biaxial electrogoniometers

4.2.2 Calibration of Electrogoniometer

Two experiments were conducted to test the general performance of the goniometer in both static and dynamic conditions. For static calibration, nine known angles (-57, -55, -40, -20, 0, 20, 40, 55, 57 degrees) in the flexion(-)/extension(+) plane, and seven known angles (-40, -20, -10, 0, 10, 20, 40 degrees) in the radial(-)/ulnar(+) plane were measured using a custom-made calibration mockup (see Figure 4.4) and the
FlexComp system (Thought Technology Ltd., NY) and its DSP board in a desktop PC (Gateway2000, Pentium PS-100). After placing the end blocks of the biaxial goniometer at a known angle on fixture, sampling began at 248 Hz for 3 seconds. A 65 msec moving average smoothing filter was applied to further condition the digitized signal. Each measurement condition was randomized and 5 trials for each plane were obtained. For dynamic calibration, the end blocks of goniometer placed on a point of known circle (37.5 or 14.4 degrees). After signal to start, the distal end block of the goniometer was rotated four times in the circle and samples were obtained using same measurement system. Data of 3 trials were measured for each circle.

Figure 4.4 Calibration mockup for electrogoniometer sensor
Results between true flexion/extension and radial/ulnar deviation angles, and goniometer measurement angles in static positions are shown in Figure 4.5(a) and Figure 4.5(b), respectively. The statistical analysis indicated that the true angles and measurements values have strong relationships across all the range of positions (p<0.001, R²=99.9% for flexion/extension and radial/ulnar deviation). Further analysis indicated that the non-repeatabilities for flexion/extension, and radial/ulnar deviation planes were 4.0%, and 3.3%, respectively, and non-linearities were 1.6%, and 0.93%, respectively. The results of non-repeatability and non-linearity of electrogoniometer in flexion/extension plane are shown in Table 4.3.
Table 4.3 Non-repeatability and non-linearity of electrogoniometer in F/E plane

<table>
<thead>
<tr>
<th>Angle</th>
<th>Non-repeatability</th>
<th>Non-linearity</th>
<th>Expected Input (N)</th>
<th>Input Deviation (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extension 57</td>
<td>0.5%</td>
<td></td>
<td>57.07</td>
<td>0.069</td>
</tr>
<tr>
<td>Extension 55</td>
<td>0.9%</td>
<td></td>
<td>54.92</td>
<td>0.076</td>
</tr>
<tr>
<td>Extension 40</td>
<td>2.9%</td>
<td></td>
<td>40.32</td>
<td>0.320</td>
</tr>
<tr>
<td>Extension 20</td>
<td>7.4%</td>
<td></td>
<td>20.02</td>
<td>0.023</td>
</tr>
<tr>
<td>Neutral 0</td>
<td>4.0%</td>
<td></td>
<td>-0.65</td>
<td>0.650</td>
</tr>
<tr>
<td>Flexion -20</td>
<td>8.4%</td>
<td></td>
<td>-21.49</td>
<td>1.493</td>
</tr>
<tr>
<td>Flexion -40</td>
<td>3.2%</td>
<td></td>
<td>-40.64</td>
<td>0.644</td>
</tr>
<tr>
<td>Flexion -55</td>
<td>0.9%</td>
<td></td>
<td>-54.37</td>
<td>0.630</td>
</tr>
<tr>
<td>Flexion -57</td>
<td>1.3%</td>
<td></td>
<td>-55.18</td>
<td>1.821</td>
</tr>
<tr>
<td>AVG</td>
<td>4.0%</td>
<td>1.6%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Non-repeatability is defined by the maximum output minus the minimum output divided by the maximum output. Non-linearity is defined by the maximum input deviation divided by the full-scale input.

Figure 4.6 shows the relationships between true flexion/extension, radial/ulnar deviation angles and goniometer measurement angles in dynamic rotation at calibration fixture radius 26.2 cm (maximum flexion or ulnar deviation angles = 37.5 degrees) and 8.8 cm (maximum flexion or ulnar deviation angles = 14.4 degrees). The regression analysis indicated that the true angles and measurements values have significant relationships across all the range (p<0.001, R²=99.8 for flexion/extension plane and radial/ulnar deviation plane). However, the goniometer measurement values appear to have wider circles than the true angle values for all ranges except for flexion angles from -13 to -36 degree, and radial angles of -11 to 35 degrees at calibration fixture radius 26.2 cm.
Regression models were developed to predict true flexion/extension angles (True_F/E), and radial/ulnar deviation angles (True_R/U) based on both measurement angles (Meas_F/E, Meas_R/U) and goniometer position at front panel (P_panel). R-squares of two regression models were 99.9%.

\[
\text{True}_F/E = -1.20 + 0.93 \text{Meas}_F/E + 0.023 \text{Meas}_R/U + 0.0029 \text{P}_\text{panel}
\]

\[
\text{True}_R/U = -0.45 + 0.025 \text{MEAS}_F/E + 0.92 \text{MEAS}_R/U
\]

In summary, the static and dynamic calibration measurements were compared to true angle data. In static positions, the biaxial goniometer was accurate and reliable. In regards to dynamic calibration, the goniometer measurement values overestimated slightly the true angle values except for small range of angles, even though the relationship was statistically significant. For this study, the mean error for flexion/extension was 2.03 degrees, and the mean error for radial/ulnar deviation was 1.08. Buchholz and Wellman (1997) reported that these values were 7.06 degrees and 5.58 degrees respectively, whereas Marshall et al. (1999) reported values of 9.67 degrees and 9.68 degrees, respectively, though they used subject's wrists instead of placing goniometer on the calibration fixture. Regression models of biaxial goniometer have been developed to correct the errors in the measurement, and significant error reduction was accomplished by using these models on data collected in the flexion/extension and radial/ulnar deviation at trials of next step.
Figure 4.6 True angles and goniometer measurement angles in dynamic rotations
4.3 Nerve Conduction Measurement

4.3.1 Electromyography (EMG) Machine

Nerve conduction studies was performed with a commercially available TECA TD-20 EMG machine (Oxford Instruments, UK) and TECA surface electrodes and stimulator as shown in Figure 4.7. The TECA-TD20 model consists of a base unit, a preamplifier and recording electrodes, and a stimulus probe. The TECA-TD20 provided factory-set filter combinations: 20 Hz to 2 kHz for surface sensory nerve action potential recordings, 2 Hz to 10 kHz for surface motor nerve action potential recordings.

Table 4.4 lists the detailed technical specifications. Standard surface electrodes includes spring-ring electrodes for digital sensory nerve action potentials recording, 1 cm discs or bar electrodes for motor nerve recording, and 3 cm discs for grounding. The surfaces electrodes are connected to base unit via a preamplifier unit (model PA89, Oxford Instruments, UK) and shields cables, and the stimulus probe is connected to base unit via a shields cable.

The cathode ray tube (CRT) of the base unit provides flicker free dual trace display. Using the averager function, the machine can display the incoming signal on the upper trace and the averaged results on the lower trace of the CRT. The base unit also contains a printer for permanent record.
Figure 4.7 Nerve conduction measurement units

Table 4.4 Technical specifications for TECA-TD20

<table>
<thead>
<tr>
<th>Technical Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Display</td>
<td>120×85 mm cathode ray tube (CRT), flicker free dual trace display</td>
</tr>
<tr>
<td>Time/div</td>
<td>Selectable from 0.2 msec/div to 100 msec/div, analysis duration = 10 div</td>
</tr>
<tr>
<td>Stimulus duration</td>
<td>0.05, 0.1, 0.2, 0.5 msec</td>
</tr>
<tr>
<td>Stimulus repetition rate</td>
<td>0.5, 1, 2, 3, 5, 10, 20, 50 pps</td>
</tr>
<tr>
<td>Stimulus intensity</td>
<td>0 to 300 V continuously adjustable</td>
</tr>
<tr>
<td>Patient leakage current</td>
<td>Less than 50 µA</td>
</tr>
<tr>
<td>Filters</td>
<td>Six settings (2Hz-10kHz, 20Hz-10kHz, 500Hz-10kHz, 20Hz-2kHz, 200Hz-2kHz, 2Hz-100Hz)</td>
</tr>
<tr>
<td>Averager gain</td>
<td>×1 to ×50</td>
</tr>
</tbody>
</table>
4.3.2 Reliability of EMG Machine

Two experiments were conducted to evaluate the performance of TECA TD-20 EMG machine on the median sensory nerve and motor nerve action potential measurements with two subjects. The nerve conduction studies were performed using the standard measurement technique described in Chapter 3.6, Figure 4.8 shows the measurement of median nerve action potentials. With wrist and digits extended so as to make the nerve segment approximate a straight, distance between stimulating and recording electrodes were marked using calipers on 14 cm from wrist to index finger for sensory nerve, 7cm from wrist to thenar muscle.

![Measurement of median nerve action potentials](image1)

(a) sensory nerve  (b) motor nerve

Figure 4.8 Measurement of median nerve action potentials
All areas on which electrodes were applied were first thoroughly cleaned with alcohol wipes to reduce resistance between contact surfaces due to skin oils, etc. The skin was allowed to dry thoroughly before applying electrodes. An active ring electrode (cathode) was placed immediately below the head of the proximal phalanx, while a reference electrode (anode) was placed 4 cm distal to the active electrode. A large ground electrode was placed on the palm between the stimulating and recording electrodes. Motor nerve responses were recorded from the belly of the abductor pollicis brevis (APB).

Five trials of onset latency, peak latency, baseline-to-negative peak amplitude, and negative peak-to-positive peak amplitude of median sensory and motor nerve were measured for each trial. Between trials, two minutes resting time was allowed.

Figure 4.9 shows the results of median sensory nerve measurements calculated across two subjects. Onset and peak latencies appear to be consistent across days and trials, while amplitudes appear to vary slightly. Analysis of variance (ANOVA) on onset latency measurements was conducted for subject, nerve type, day and trial variables, with the results shown in Table 4.5. The median nerve onset latency significantly varied for nerve type (F=868.97, P<0.001) and subjects (F=43.83, P<0.001), but were consistent across day (F=1.56, P>0.05) and trial (F=0.05, P>0.05).
Figure 4.9 Reliability of sensory nerve conduction measurements

Table 4.5 ANOVA for median nerve onset latency responses

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUBJECT</td>
<td>1</td>
<td>1.0962</td>
<td>1.0962</td>
<td>43.83</td>
<td>0.000</td>
</tr>
<tr>
<td>NERVE</td>
<td>1</td>
<td>21.7322</td>
<td>21.7322</td>
<td>868.97</td>
<td>0.000</td>
</tr>
<tr>
<td>DAY</td>
<td>2</td>
<td>0.0782</td>
<td>0.0391</td>
<td>1.56</td>
<td>0.219</td>
</tr>
<tr>
<td>TRIAL</td>
<td>4</td>
<td>0.0052</td>
<td>0.0013</td>
<td>0.05</td>
<td>0.995</td>
</tr>
<tr>
<td>Error</td>
<td>51</td>
<td>1.2755</td>
<td>0.0250</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>59</td>
<td>24.1873</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 5
EXPERIMENTAL METHODS

5.1 Experimental Objectives

The goal of this experiment is to determine if a measurable change in median nerve function can be systematically produced with exposure to dynamic wrist workloads. If achieved, this facilitates the development of quantitative dose-response relationship between occupational risk factors and CTS prevalence.

5.2 Dynamic Wrist Workloads Conditions

As mention in Chapter 2, the work-related risk factors which are associated with development of CTS include repetitive motions, forceful exertion, awkward postures, localized contact stresses, vibration, and cold temperature. In this study, the wrist workloads consist of the forceful exertions and repetitive wrist movements with awkward wrist posture for prolonged periods.
5.2.1 Repetitive Movements

Numerous epidemiological studies reported that highly dynamic repetitive wrist motions have a strong positive association with the prevalence of CTS as discussed early in Chapter 2. The repetitive wrist movements which are defined as repetitions per minute (RPM) can be broken into cyclic wrist motions as shown in Figure 5.1, where the wrist movements resemble sinusoidal waveforms. Although slight differences between two waveforms are due to irregularities in human hand motion, the wrist movements appear to be similarly sinusoidal.

Figure 5.1 Wrist motions and sin waveform
Based on this assumption, the angular accelerations of sine waveforms with angular displacement of 120 degrees were calculated for 20 to 60 repetitions per minute (RPM). Values of 22 RPM and 50 RPM, corresponding to the mean acceleration levels of 200 and 1050 degrees/sec², were selected as two levels of independent variable for repetitive movements (see Table 5.1). These were defined as low and high repetition workload conditions in this study. Marras and Schoenmarklin (1993) defined low risk jobs as those tasks producing mean angular accelerations less than 490 degree/sec², and high risk as those tasks producing mean angular accelerations greater than 820 degrees/sec². Therefore, the classification of the low and high repetition tasks used in this study is not different from previous studies.

A 120 degree range of angular displacement was used during repetitive flexion/extension movements. This consisted of 60 degrees of flexion and 60 degrees of extension and corresponded to previous studies for maximum range of motions (see Table 5.2). Feedback of angular displacement was provided on a computer monitor.

Table 5.1 Low and high repetition and angular acceleration

<table>
<thead>
<tr>
<th>RPM (repetitions per min)</th>
<th>Velocity (degrees/sec)</th>
<th>Acceleration (degrees/sec²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Peak</td>
</tr>
<tr>
<td>22 (Low)</td>
<td>89.3</td>
<td>138.2</td>
</tr>
<tr>
<td>50 (High)</td>
<td>199.1</td>
<td>314.2</td>
</tr>
</tbody>
</table>
Table 5.2 Maximum range of motions of wrist joints

<table>
<thead>
<tr>
<th>Previous studies</th>
<th>Maximum Wrist Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flexion</td>
</tr>
<tr>
<td>Boone et al. (1979)</td>
<td>76</td>
</tr>
<tr>
<td>Bonebrake et al. (1990)</td>
<td>86</td>
</tr>
<tr>
<td>Schoenmarklin and Marras (1993)</td>
<td>62</td>
</tr>
</tbody>
</table>

5.2.2 Forceful Exertion

Manual tasks in manufacturing and production environments often require an exertion of high pinch or grip forces on hand tools or workplaces. These are often within very short cycle times, amounting to thousands of forceful pinches per day (Kroemer, 1989). The pinching and fingertip pressing tasks also produce large carpal tunnel pressures for relatively low external forces (Keir et al., 1998b). Moreover, internal loading induced during pinching tasks is near twice that of fingertip pressing tasks for identical external forces, where use of pinch hand postures can result in up to 50 percent more force in the first and second flexor tendons adjacent to the median nerve (Chao, 1976; Smith et al., 1977). Based on these backgrounds, pinch grip task is chosen as a workload task condition for forceful exertions in this study.

Since pinching tasks usually require intermittent forces, repetitively grasping and releasing loads or products rather than continuous and static holding forces, a similar forceful exertion workload was presented to the subjects. Figure 5.2 shows the pinch
force exertion method during repetitive wrist movements. Subjects were asked to exert a target pinch force in wrist flexion and release the force in wrist extension while holding the hand tool and moving the wrist. In order to help subject exert periodically a target force value, visual and auditory feedback of force exertion was provided to subjects using a computer screen, with a preset upper threshold limit and auditory feedback when subjects exceeded the force level.

The target pinch force was set at level proportional to the maximum pinch grip strength for each subject. Two conditions, no force (0%) and 20% of maximum pinch force (20%MVC, Maximum Voluntary Contraction) were chosen as levels of the independent variable for forceful exertion. A target value of 20% was selected so as to induce muscle fatigue and possible changes in nerve conduction measures.

Pinch force exertion was performed using a manipulation hand tool, which was developed and evaluated with one subject in pilot study. But, an informal discussion with the subject discovered that the handle was too large and heavy for long period force exertions. A smaller size device (i.e. lighter weight) was developed as shown in Figure 5.3. Pinch force was measured on the middle of the simulated tool by a FlexiForce sensor attached on inner side of a wood shaft. The force sensor was mounted over the point of force application for the thumb and index finger of the one-point pulp pinch.
Figure 5.2 Pinch force exertion method during repetitive wrist motions (50 RPM)

Figure 5.3 A hand tool for pinch force exertions
5.3 Experimental Design

The effect of forceful exertion and repetitive movement on nerve conduction function was examined using $2^2$ factorial design techniques. The levels of the each factor were called "low" and "high" conditions as shown in Table 5.3.

The two levels of repetitive movements were controlled by the auditory beat sound of a metronome (AccuTech Metrotuner, Model MT-6000). Pinch force exertion was controlled by changing the threshold visual and auditory feedback to subjects. The presentation order of the workload conditions to subjects was randomized.

Each session lasted three hours. Considering muscle fatigue from task performance and the long experimental time, only one session was performed per day for each subject. Typically, subjects were provided at least 3 days rest between sessions.

<table>
<thead>
<tr>
<th>Wrist workload conditions</th>
<th>Repetitive movements</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>(22 RPM, or</td>
<td>(50 RPM, or</td>
</tr>
<tr>
<td></td>
<td>acceleration of 200°/sec²)</td>
<td>acceleration of 1,050°/sec²)</td>
</tr>
<tr>
<td>Force exertion</td>
<td>Low</td>
<td>Low-Force, Low-Repetition (LOF.LOR)</td>
</tr>
<tr>
<td>(pinch force)</td>
<td>(0% MVC, or no force)</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>Low-Force, Low-Repetition (LOF.LOR)</td>
<td>Low-Force, High-Repetition (LOF.HIR)</td>
</tr>
<tr>
<td>High</td>
<td>High-Force, Low-Repetition (HIF.LOR)</td>
<td>High-Force, High-Repetition (HIF.HIR)</td>
</tr>
<tr>
<td>(20% MVC)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.4 Variables

5.4.1 Independent Variables

The following independent variables were monitored and recorded as measures of dynamic wrist workloads of forceful exertion and repetitive movement:

- Mean pinch force (N)
- Maximum pinch force (N)
- Mean angular flexion/extension (degrees)
- Maximum angular flexion/extension (degrees)
- Maximum flexion/extension range of motions (degrees)
- Mean angular velocity (degrees/sec)
- Maximum angular velocity (degrees/sec)
- Mean angular acceleration (degrees/sec²)
- Maximum angular acceleration (degrees/sec²)
- Perceived subjective comfort using the Borg CR-10 rating scale of perceived exertion (RPE). The CR-10 scale is a category rating with ratio properties for subjective assessments of perceived intensity (Borg, 1982).

5.4.2 Dependent Variables

The following nerve conduction measurements for median sensory and motor nerve were monitored and recorded every 20 minutes using the EMG machine during task performance.
• Onset latency (msec): time between nerve stimulation and initial response detected at the active recording electrode.

• Peak latency (msec): time between nerve stimulation and peak response detected at the active recording electrode.

• Onset amplitude (mV for motor NCS; µV for sensory NCS): height of the waveform between onset and the peak response of negative spike.

• Peak amplitude (mV for motor NCS; µV for sensory NCS): height of the waveform between the peak response of negative spike (Peak) and the peak response of positive spike (Trough).

• Conduction velocity (m/sec): calculated by dividing stimulated nerve length by onset latency for median sensory nerve conduction.

5.4.3 Confounding Variables

Room temperature of the experimental environment in which data collection was conducted was monitored and controlled as best as possible between 19 and 25°C (66~76°F). Because skin temperature has a profound effect on nerve conduction parameters (Letz and Gerr, 1994; Baysal et al., 1993), the skin temperature on palmer side of hand was carefully monitored and kept above 31°C using heater or radiator if necessary.
5.5 Sample Size and Subject Recruitment

5.5.1 Sample Size Determination

Sample size, the number of participants to be recruited in this study, was determined by considering type I error rate (\( \alpha \)), type II error rate (\( \beta \)), variability of measurement (\( \sigma \)), and expected difference between two treatment means (\( D \)). The parameter of equation 5.1 was used to determine the sample size (Montgomery, 1991).

\[
\Phi^2 = \frac{nbD^2}{2a\sigma^2}
\]  
(Equation 5.1)

The null hypothesis for workload conditions being tested is the equivalence of two levels of each workload condition. Given a minimum acceptable power of 0.80 (the probability of rejecting the null hypothesis if the alternative hypothesis is true), a significance level of \( \alpha = 0.05 \), and five percent expected change for mean value in nerve conduction measure (i.e. median nerve sensory onset latency), power analysis as shown in Table 5.4 determined that a minimum sample size 13 subjects is necessary to detect a statistically significant effect. The expected change (\( D=0.12 \) msec) was determined by using the mean median sensory nerve onset latency (2.43 msec) of pilot study described in Chapter 4.3 and 5 percent expected change (2.43×0.05=0.12 msec). The variability of measurement (\( \sigma = 0.15 \) msec) also based on the mean standard deviation of the onset latency of the pilot study.
Table 5.4 Power analysis for determining sample size

<table>
<thead>
<tr>
<th>N (sample size)</th>
<th>Parameters</th>
<th>Degree of Freedom</th>
<th>Error</th>
<th>Power (1-β)</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Φ²</td>
<td>Φ v₁ (Numerator)</td>
<td>v₂ (Denominator)</td>
<td>α (Type I)</td>
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<td>1.81</td>
<td>1</td>
<td>0.05</td>
</tr>
<tr>
<td>11</td>
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<td>1.90</td>
<td>1</td>
<td>0.05</td>
</tr>
<tr>
<td>12</td>
<td>3.94</td>
<td>1.98</td>
<td>1</td>
<td>0.05</td>
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<tr>
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<td>2.07</td>
<td>1</td>
<td>0.05</td>
</tr>
<tr>
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<td>0.05</td>
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<tr>
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<td>0.05</td>
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<tr>
<td>16</td>
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<td>2.29</td>
<td>1</td>
<td>0.05</td>
</tr>
<tr>
<td>17</td>
<td>5.58</td>
<td>2.36</td>
<td>1</td>
<td>0.05</td>
</tr>
<tr>
<td>18</td>
<td>5.90</td>
<td>2.43</td>
<td>1</td>
<td>0.05</td>
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<tr>
<td>19</td>
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<td>20</td>
<td>6.56</td>
<td>2.56</td>
<td>1</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Note: Φ² = (nbD²)/(2aσ²), a=2, b=2, D=0.12, σ=0.15, v₁=a-1, v₂=ab(n-1)

5.5.2 Subject Recruitment

Fifteen subjects between the ages of 19 and 35 were recruited for this study from a student population without any hand surgeries which might limit their physical activities. They were screened for any hand and wrist injuries or any hand surgery using the questionnaire in Appendix B. They were compensated for their participations in four workload sessions required approximately 4 hours for each workload session, and provided voluntary informed consent.

Mean age of these subjects was 30.3 years (SD = 4.0), and two of them were female. The right hand was dominant in 13 of the 15 participants. Demographic and grip
strength data such as gender, age, maximum grip strength, and maximum pinch grip strength of the experimental subjects listed in Table 5.5.

Maximum power grip strength and maximum one-point pinch grip strength were measured before the main nerve conduction experiment started. This regimen involved three seconds ramps to peak, a one-minute break between trials, and used an average of three trials as a measure of maximum force. The 20 percent pinch force (20%MVC) of subject’s maximum voluntary pinch force was used as a target pinch force level for high force wrist workload condition of each subject.

Table 5.5 Experimental subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>General Demographics</th>
<th>Maximum Grip Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>gender</td>
<td>age</td>
</tr>
<tr>
<td>1</td>
<td>JYW</td>
<td>M</td>
</tr>
<tr>
<td>2</td>
<td>CWL</td>
<td>M</td>
</tr>
<tr>
<td>3</td>
<td>MCJ</td>
<td>M</td>
</tr>
<tr>
<td>4</td>
<td>CXL</td>
<td>M</td>
</tr>
<tr>
<td>5</td>
<td>JDK</td>
<td>M</td>
</tr>
<tr>
<td>6</td>
<td>JHJ</td>
<td>M</td>
</tr>
<tr>
<td>7</td>
<td>YHH</td>
<td>M</td>
</tr>
<tr>
<td>8</td>
<td>SYL</td>
<td>M</td>
</tr>
<tr>
<td>9</td>
<td>JIP</td>
<td>M</td>
</tr>
<tr>
<td>10</td>
<td>SCL</td>
<td>M</td>
</tr>
<tr>
<td>11</td>
<td>TKK</td>
<td>M</td>
</tr>
<tr>
<td>12</td>
<td>DMS</td>
<td>M</td>
</tr>
<tr>
<td>13</td>
<td>MAM</td>
<td>F</td>
</tr>
<tr>
<td>14</td>
<td>SSP</td>
<td>M</td>
</tr>
<tr>
<td>15</td>
<td>MJK</td>
<td>F</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td></td>
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<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Anthropometric characteristics of the experimental subjects are listed in Table 5.6. Average weight and height of experimental subjects were 67 Kg (range 55 - 81), and 1731 mm (range 1680 – 1830), respectively. Average Body Mass Index (BMI) calculated by weight in kilograms divided by the square of height in meters was 22 (range 19 - 28). Hand length averaged 189 mm (range 179-220), while wrist breadth had a mean of 57 mm (range 53-63).

Table 5.6  Antropometric variables measured on subjects’s hand

<table>
<thead>
<tr>
<th>Subject</th>
<th>weight (kg)</th>
<th>statue (mm)</th>
<th>BMI (kg/m²)</th>
<th>hand length (mm)</th>
<th>hand breadth (mm)</th>
<th>hand thickness (mm)</th>
<th>wrist breadth (mm)</th>
<th>wrist depth (mm)</th>
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<tbody>
<tr>
<td>1</td>
<td>JYW</td>
<td>64</td>
<td>1730</td>
<td>21</td>
<td>191</td>
<td>86</td>
<td>34</td>
<td>55</td>
</tr>
<tr>
<td>2</td>
<td>CWL</td>
<td>69</td>
<td>1730</td>
<td>23</td>
<td>179</td>
<td>83</td>
<td>31</td>
<td>54</td>
</tr>
<tr>
<td>3</td>
<td>MCJ</td>
<td>55</td>
<td>1720</td>
<td>19</td>
<td>187</td>
<td>81</td>
<td>32</td>
<td>54</td>
</tr>
<tr>
<td>4</td>
<td>CXL</td>
<td>62</td>
<td>1720</td>
<td>21</td>
<td>183</td>
<td>84</td>
<td>35</td>
<td>57</td>
</tr>
<tr>
<td>5</td>
<td>JDK</td>
<td>63</td>
<td>1740</td>
<td>21</td>
<td>199</td>
<td>85</td>
<td>34</td>
<td>55</td>
</tr>
<tr>
<td>6</td>
<td>JHJ</td>
<td>66</td>
<td>1700</td>
<td>23</td>
<td>183</td>
<td>88</td>
<td>33</td>
<td>56</td>
</tr>
<tr>
<td>7</td>
<td>YHH</td>
<td>64</td>
<td>1700</td>
<td>22</td>
<td>183</td>
<td>77</td>
<td>28</td>
<td>53</td>
</tr>
<tr>
<td>8</td>
<td>SYL</td>
<td>68</td>
<td>1800</td>
<td>21</td>
<td>192</td>
<td>83</td>
<td>32</td>
<td>60</td>
</tr>
<tr>
<td>9</td>
<td>JIP</td>
<td>75</td>
<td>1800</td>
<td>23</td>
<td>220</td>
<td>85</td>
<td>34</td>
<td>58</td>
</tr>
<tr>
<td>10</td>
<td>SCL</td>
<td>70</td>
<td>1700</td>
<td>24</td>
<td>185</td>
<td>87</td>
<td>35</td>
<td>57</td>
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<tr>
<td>11</td>
<td>TKK</td>
<td>81</td>
<td>1710</td>
<td>28</td>
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<td>89</td>
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<td>12</td>
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<td>1680</td>
<td>22</td>
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<td>86</td>
<td>33</td>
<td>57</td>
</tr>
<tr>
<td>13</td>
<td>MAM</td>
<td>63</td>
<td>1700</td>
<td>22</td>
<td>179</td>
<td>80</td>
<td>29</td>
<td>60</td>
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<tr>
<td>14</td>
<td>SSP</td>
<td>78</td>
<td>1830</td>
<td>23</td>
<td>191</td>
<td>91</td>
<td>33</td>
<td>60</td>
</tr>
<tr>
<td>15</td>
<td>MJK</td>
<td>59</td>
<td>1700</td>
<td>20</td>
<td>184</td>
<td>82</td>
<td>26</td>
<td>56</td>
</tr>
<tr>
<td>Mean</td>
<td>67</td>
<td>1731</td>
<td>22</td>
<td>189</td>
<td>84</td>
<td>32</td>
<td>57</td>
<td>40</td>
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<tr>
<td>SD</td>
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<td>2.1</td>
<td>10.4</td>
<td>3.6</td>
<td>2.6</td>
<td>2.6</td>
<td>1.6</td>
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<tr>
<td>Minimum</td>
<td>55</td>
<td>1680</td>
<td>19</td>
<td>179</td>
<td>77</td>
<td>26</td>
<td>53</td>
<td>37</td>
</tr>
<tr>
<td>Maximum</td>
<td>81</td>
<td>1830</td>
<td>28</td>
<td>220</td>
<td>91</td>
<td>35</td>
<td>62</td>
<td>42</td>
</tr>
</tbody>
</table>
5.6 Data Collection Procedure

5.6.1 Wrist Workload Measures

Wrist workloads were monitored and recorded by using the FlexComp system, biaxial electrogoniometer and force sensor attached in hand tool. The goniometer was attached on a subject's right forearm and hand using two points, the third metacarpal and the dorsal center of the wrist. After attaching the telescopic endblock to hand, subject was asked to fully flex the wrist, while goniometer was extended and the flexed endblock was attached to the forearm. For grasp method of the handle, the subject was asked to hold the simulated hand tool using right thumb fingertip and index fingertip.

Simple calibration procedures for zeroing of the electrogoniometer and force sensor signals were required before measurement. Telescopic and fixed endblocks of the goniometer were laid flat and straight against a rigid edge for period of 10 seconds to zero the electrogoniometer signal. The force sensor was laid flat without loads for the same time period to zero it.

Although visual and auditory feedback was provided to subjects for whole task period, the data was recorded for first ten minutes and last ten minutes of task performance. All data was sampled at 248 Hz.
5.6.2 Nerve Conduction Measures

The nerve conduction measures were recorded using the standard measurement technique described in Chapter 3.6. With wrist and digits were extended so as to make the nerve segment approximate a straight, distance between stimulating and recording electrodes was marked using calipers on 14 cm from wrist to index finger for sensory nerve, 7 cm from wrist to thenar muscle (the abductor pollicis brevis) for motor nerve.

All areas on which electrodes were applied were first thoroughly cleaned with alcohol wipes to reduce resistance between contact surfaces due to skin oils, etc. The skin was allowed to dry thoroughly before applying electrodes. For sensory nerve conduction recording, an active ring electrode (cathode) was placed below the head of the proximal phalanx of index finger, and reference electrode (anode) was placed 4 cm distal to the active electrode. For motor nerve response, an active disc electrode (cathode) was placed on the belly of the abductor pollicis brevis (APB), and reference electrode (anode) was placed on tendon of APB muscle, approximately 4 cm distal to active electrode. For both sensory and motor nerve recordings, a large ground electrode was placed on the palm between the stimulating and recording electrodes (see Figure 5.4).
All nerve conduction measurements were recorded in response to supramaximal constant voltage stimulation with 0.1 msec of stimulus duration and 1 pps (repetition per second) stimulus frequency rate. The stimulus level was determined for each subject at by increasing and reapplying a stimulus antidromically along the median nerve fibers, until a clearly defined action potential response is produced. The resultant waveform of the nerve action potential was recorded as the baseline measure. Filter setting was 20 Hz to 2
kHz for surface sensory nerve action potential recordings, and 2 Hz to 10 kHz for surface motor nerve action potential recordings.

The nerve conduction measures were recorded immediately before the start of the task and every 20 minutes thereafter during the task performance.

5.6.3 Skin Temperature Measures

Since the correlation between median nerve function and skin temperature is widely reported, the skin temperature was monitored and recorded on palmar surface of metacarpal phalangeal joint of index finger using Digital Pyrometer (Newport Electronics, Inc, Santa Ana, CA). A minimum skin temperature of 31°C (Jackson and Clifford, 1989) was maintained using heated water or radiator before task performance, if necessary.

Like nerve conduction measures, the skin temperature was recorded immediately before task starts and every 20 minutes therefore during task performance.

5.6.4 Data Collection Protocol

Each participant first read and signed an informed consent form. The investigator also explained the study to him/her regarding purpose, procedure, time duration, and confidentiality, reviewing the contents of informed consent form. Prior to starting the study, the investigator emphasized that he/she would withdraw from this study at any time. Following signing the consent form, the participant was asked to complete a
screening questionnaire, and then anthropometric data such as height, weight, and hand size was measured.

This study was conducted individually in a temperature controlled room. Each participant was assisted by investigator to sit with upper arm vertical, forearm horizontal, elbow 90 degrees to the body. The forearm was placed in a neutral position such that the wrist flexion/extension movement was performed in the horizontal plane. A strap was secured across the subject's mid forearm to minimize arm movement during task performance.

After attaching electrogoniometer sensor and disposal electrodes on participant's right wrist and hand as explained earlier, subjects performed repetitive wrist/hand movements of 120 degrees in the flexion and extension plane following auditory beat sounds (22 RPM or 50 RPM). During the repetitive wrist movements, subject also exerted intermittently the target force (20% MVC or 0% MVC) as the wrist was flexed, using the fingertips of the right thumb and index finger to grip the simulated hand tool. Feedback of pinch force exertions and angular displacement was provided on the computer screen.

The four workload conditions were presented randomly to each subject, one per day. The workload was recorded during the first ten minutes and last ten minutes of the task. Nerve conduction functions and skin temperature were measured every 20 minutes throughout task performance. Subjects were also asked to rate their perceived comfort level, using the Borg CR-10 rating scale at the end of the task.
When the participant completed the study, he/she was asked to give any comments or questions concerning this study. Finally, the investigator thanked the participants for voluntarily participating in the survey.

5.7 Data Analysis

Repeated measures analysis of variance (ANOVA) with subjects serving as their own controls was used to determine the effect of each factor, and interaction on nerve conduction function. Changes in median nerve conduction measures were summarized using descriptive statistics and presented graphically. A post-hoc paired comparison test was used to further explore the statistical significance. Pearson’s correlation and linear regression analyses were also used to evaluate the relationship between independent and dependent variables. All statistical analyses were performed by MINITAB™ (release 13.1) statistical software.
Chapter 6

RESULTS

6.1 Wrist Workload during Task Performance

6.1.1 Forceful Exertion

Figure 6.1 shows the mean and maximum pinch force exertion calculated across participants for force exertion conditions. Mean pinch force was higher for high repetition condition (high force-high repetition (20% MVC, 50RPM; HIF.HIR): 4.8N) compared to the low repetition condition (high force-low repetition (20% MVC, 22RPM; HIF.LOR): 3.1N). This difference was statistically significant ($F_{1,28} = 11.52$, $p = 0.002$). Maximum forces for HIF.LOR and HIF.HIR were 26.9, and 27.5 N, respectively, and not significantly different ($F_{1,28} = 0.05$, $p = 0.83$).

Figure 6.1 Results of pinch force exertion
(each bar represents the respective standard error)
6.1.2 Wrist Flexion/Extension Angle

Mean and maximum wrist flexion/extension angles were calculated across participants for each condition, the results are shown in Figure 6.2. Maximum angular flexion was higher for low force conditions (low force-low repetition (0%MVC, 22RPM; LOF.LOR): -68.5°; low force-high repetition (0%MVC, 50RPM; LOF.HIR): -66.9°) compared to the high force conditions (high force-high repetition (20%MVC, 50RPM; HIF.HIR): -44.5°; high force-low repetition (20%MVC, 22RPM; HIF.LOR): -54.0°). This may indicate a natural tendency to reduce tensile strain on the median nerve and tendons when participants performed pinch force exertions for the high force conditions. The repeated measures analysis of variance revealed that the effects on maximum flexion angle of force, and repetition, and force \times repetition interaction term were significant (see Table 6.1). Especially, within subject variability, the force factor accounted for 72% of the total sum of squares.

Maximum angular extensions were 72.7°, 76.3°, 65.0° and 71.3° for LOF.LOR, HIF.LOR, LOF.HIR, and HIF.HIR conditions, respectively. As seen in Table 6.2, the results of the repeated measures analysis of variance for maximum extension found the main effects of force, and repetition to be significant, but the interaction of these was not significant (F_{1,42} = 0.65, p = 0.426). The total range of motion summed over each condition was ordered by LOF.LOR (141.2°), LOF.HIR (131.9°), HIF.LOR (130.3°), and HIF.HIR (115.8°). Figure 6.3 shows the range of motions over each workload condition.
Figure 6.2 Results of wrist flexion/extension movement (each bar represents the respective standard error)

### Table 6.1 ANOVA for maximum flexion

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
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<td>SUBJECT</td>
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<td>321.49</td>
<td>10.66</td>
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<td>5082.63</td>
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<td>30.15</td>
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<td></td>
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<td>Total</td>
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<td>11544.64</td>
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### Table 6.2 ANOVA for maximum extension

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<th>MS</th>
<th>F</th>
<th>P</th>
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<td>365.12</td>
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<td>601.22</td>
<td>14.59</td>
<td>0.000 *</td>
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<td>26.63</td>
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<td>0.426</td>
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Figure 6.3 Maximum range of motion for wrist flexion/extension movement
(each bar represents the respective standard error)
6.1.3 Wrist Angular Velocity

Figure 6.4 shows the mean and maximum wrist flexion/extension angular velocities calculated across participants for each condition. As expected, mean angular velocities for high repetition conditions (LOF.HIR: 184.2°/sec; HIF.HIR: 140.7°/sec) were higher than those for low repetition (LOF.LOR: 97.8°/sec; HIF.LOR: 84.9°/sec). The repeated measures analysis of variance indicated that mean wrist velocity significantly affected by force, repetition, and force × repetition interaction (see Table 6.3). Within subject variability, the repetition factor accounted for 80.2% of the total sum of squares.

The maximum velocity showed responses similar to the results of mean velocity. Maximum angular velocity for high repetition conditions were 394.1°/sec, and 342.1°/sec for LOF.HIR and HIF.HIR, respectively, while for low repetition conditions maximum velocity were 282.9°/sec, and 252.4°/sec for LOF.LOR and HIF.LOR, respectively. The repeated measures analysis of variance for maximum velocity is presented in Table 6.4.
Figure 6.4 Results of wrist flexion/extension angular velocity
(each bar represents the respective standard error)

Table 6.3 ANOVA for mean F/E angular velocity

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Table 6.4 ANOVA for maximum F/E angular velocity

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6.1.4 Wrist Angular Acceleration

The mean and maximum wrist flexion/extension angular acceleration calculated across participants for each condition, the results are shown in Figure 6.5. Like angular velocity results, mean angular accelerations were higher for high repetition conditions (LOF.HIR: 781.0°/sec²; HIF.HIR: 593.2°/sec²) compared to those for low repetition (LOF.LOR: 271.5°/sec²; HIF.LOR: 231.2°/sec²). The repeated measures analysis of variance seen in Table 6.5 also revealed results similar to the angular velocity that mean wrist acceleration significantly affected by force, repetition, and force \( \times \) repetition interaction.

The maximum acceleration also showed responses similar to the results of maximum velocity. Maximum angular acceleration for high repetition conditions were 1617.1°/sec², and 1406.0 °/sec² for LOF.HIR and HIF.HIR, respectively, while for high repetition conditions maximum acceleration were 772.4°/sec², and 640.0 °/sec² for LOF.LOR and HIF.LOR, respectively. The repeated measures analysis of variance for maximum acceleration is presented in Table 6.6.
Figure 6.5 Results of wrist flexion/extension angular acceleration
(each bar represents the respective standard error)

Table 6.5 ANOVA for mean F/E angular acceleration

<table>
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Table 6.6 ANOVA for maximum F/E angular acceleration

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6.1.5 Cumulative Time and Angle-Time Exposure during Wrist F/E Movement

Cumulative time during wrist movement represents the accumulated exposure time when participants performed wrist movement beyond neutral position. As seen in the Figure 6.6, the cumulative time is defined as the time interval that the wrist exceeds a threshold deviation angle summed over the three hours of task performance. Cumulative angle-time exposure is defined as the product of the time interval times the threshold angle.

Figure 6.6 Definition of cumulative time and cumulative angle-time exposure
Figure 6.7 and Figure 6.8 show the cumulative time and cumulative angle-time exposure calculated across participants for each condition with different thresholds of 30°, 35°, 40°, and 45°. As expected, the cumulative time and cumulative angle-time exposure for a threshold flexion/extension angle of 30° was higher than that for a threshold angle of 45°. The cumulative time was highest in LOF.LOR, followed by LOF.HIR, HIF.LOR, and HIF.HIR for 30°, 35° and 40° thresholds, while for 45° threshold, the order was LOF.LOR, HIF.LOR, LOF.HIR, and HIF.HIR. This result was similar to the result of total range of motion where the order was LOF.LOR (141.2°), LOF.HIR (131.9°), HIF.LOR (130.3°), and HIF.HIR (115.8°). Similar to cumulative time, cumulative angle-time exposure was highest in LOF.LOR condition, followed by HIF.LOR, LOF.HIR, and HIF.HIR conditions.

The repeated measures analysis of variance on cumulative time and cumulative angle-time exposure are listed in Table 6.7 and Table 6.8, respectively. The results indicated that the main effects of force and repetition on cumulative time were significant for all thresholds, but the interaction effect of force × repetition was significant for only 30° and 55° thresholds.
Figure 6.7 Results of cumulative time
(each bar represents the respective standard error)

Table 6.7 ANOVA summary for cumulative time

<table>
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<tr>
<th>Source</th>
<th>Cumulative time for F/E angle &gt; 30°</th>
<th>Cumulative time for F/E angle &gt; 35°</th>
<th>Cumulative time for F/E angle &gt; 40°</th>
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<td>F</td>
<td>p</td>
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Note: “ns” means not significant
Figure 6.8 Results of cumulative angle-time exposure (each bar represents the respective standard error)

Table 6.8 ANOVA summary for cumulative angle-time exposure

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<th>Source</th>
<th>Cumulative Angle-time Exposure for F/E angle &gt; 30°</th>
<th>Cumulative Angle-time Exposure for F/E angle &gt; 35°</th>
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<th>Cumulative Angle-time Exposure for F/E angle &gt; 45°</th>
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<td><strong>F</strong></td>
<td><strong>p</strong></td>
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Note: “ns” means not significant
6.1.6 Rating of Perceived Exertion (RPE)

Rating of perceived exertion (RPE) is the perceived subjective comfort using the Borg’s CR-10 rating scale of perceived exertion where the CR-10 scale is a category rating with ratio properties for subjective assessment of perceived intensity. Figure 6.9 shows the results of RPE calculated across participants for each condition. The results indicated that RPE was greater for high force conditions (HIF.HIR: 6.9; HIF.LOR: 4.7) compared to those of low force condition (LOF.HIR: 3.5; LOF.LOR: 2.1). The repeated measures analysis of variance indicated that the RPE significantly affected by force, and repetition (see Table 6.9). It is also interested to note that the RPE for high repetition conditions were higher than that of low repetition conditions.

![Figure 6.9 Results of rating of perceived exertion survey](image)

Figure 6.9 Results of rating of perceived exertion survey (each bar represents the respective standard error)
Table 6.9 ANOVA for rating of perceived exertion

<table>
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6.2 Median Sensory Nerve Conduction Change during Three Hours Workload

6.2.1 Onset Latency and Peak Latency

The median sensory nerve onset latencies and peak latencies recorded immediately before and every 20 minutes during the three hours of task performance are shown in Figure 6.10 and Figure 6.11. The standard errors across 15 participants are also presented for each workload condition. The results indicated that mean initial onset latencies at time = 0 across participants were similar across workload conditions (F_{3,56}=0.80, p=0.497), however exposure to wrist workload produced a noticeable difference in onset latency. Onset latencies for LOF.LOR, HIF.LOR, and LOF.HIR conditions increased during task performance, while little change was found for HIF.HIR. Onset latencies for LOF.LOR, HIF.LOR, and LOF.HIR conditions also showed high standard errors. Peak latencies over time showed responses very similar to onset latencies, due to their highly correlated relationship shown in Figure 6.12.
Figure 6.10 Onset latency during three hours of task performance
(each bar represents the respective standard error)
Figure 6.11 Peak latency during three hours of task performance
(each bar represents the respective standard error)
The repeated measures analysis of variance on onset latency and peak latency were conducted to investigate the strength of association between the nerve conduction measures and subject, force, repetition, and time, with the results shown in Table 6.10, and Table 6.11, respectively. Significant main effects for onset latency were detected for subject (F=28.79, p<0.001), force (F=134.82, p<0.001), repetition (F=96.67, p<0.001), and time (F=13.94, p<0.001). There was also a weak significant force × time interaction effect (F=3.29, p<0.01). The repeated measures analysis of variance on peak latency produced similar statistical findings with onset latency.
However, the results also revealed that the latency change in low force conditions were significant greater than those in high force conditions, and the latency change in low repetition conditions were significant larger than those in high repetition conditions. These were totally unexpected results, because the principle hypothesis of this study was that median nerve function decreases as wrist workloads increases. It is therefore postulated that the observed effects of force and repetition on latency change may be partly due to the interaction of workload, heat gain and air flow to the hand, with changes in skin temperature affecting nerve conduction measures.

<table>
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Post-hoc paired comparisons on time (i.e. duration of exposure) were performed separately for each workload condition using Tukey Simultaneous Tests (at $\alpha=0.05$) to further explore the changes in onset latency and peak latency from the initial baseline measures (i.e. time = 0). The results presented in Table 6.12 indicated that significant changes in onset latency due to the LOF.LOR condition first occurred 60 minutes into task performance. Also onset latencies after 160 minutes were significantly different from onset latencies after 60 minutes, while onset latencies between 60 and 140 minutes were statistically undifferentiated. For HIF.LOR and LOF.HIR conditions, the significant changes in onset latency were first noted after 60 minutes of exposure to wrist workload, while onset latencies for HIF.HIR were not statistically different during the three hours of task performance.

Post-hoc paired comparisons on time (i.e. duration of exposure) for peak latency also produced very similar results (see Table 6.13). Significant changes in peak latency for the LOF.LOR, HIF.LOR, and LOF.HIR conditions first occurred after 60 minutes of exposure, while peak latency for HIF.HIR did not statistically change during the three hours of task performance.
### Table 6.12 Pairwise comparison for time on onset latency

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<th>60</th>
<th>80</th>
<th>100</th>
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<th>140</th>
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Note: Underlining (thin or thick) pairs mean ‘not significantly different’, and thicker lines represent “significant differences” to thin lines.

### Table 6.13 Pairwise comparison for time on peak latency

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<th>160</th>
<th>180</th>
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<td>LOF.LOR</td>
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<tr>
<td>LOF.HIR</td>
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<td>HIF.HIR</td>
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</tbody>
</table>

Note: Underlining (thin or thick) pairs mean ‘not significantly different’, and thicker lines represent “significant differences” to thin lines.
6.2.2 Conduction Velocity

Median sensory nerve conduction velocity was calculated as the ratio of the stimulated nerve length from the stimulus point to the recording point and the latency of nerve conduction between them. Onset latency is typically used for this measure. With nerve length constant, conduction velocity measures should produce results very similar to onset latency as evidenced by the Pearson correlation between conduction velocity and onset latency of -0.993 (p<0.001). The results of median sensory nerve conduction velocity are presented in Figure 6.13.
Figure 6.13 Conduction velocity during three hours of task performance
(each bar represents the respective standard error)
6.2.3 Amplitude

Figure 6.14 and Figure 6.15 show the results of median sensory nerve onset amplitude (amplitude of onset to negative peak) and peak amplitude (amplitude of negative to positive peak) during the three hours of task performance calculated across participants for each condition. The graphical explanations of onset amplitude and peak amplitude were shown in Figure 3.2. The standard error bars across 15 participants are also presented for each workload condition. Overall increases of amplitudes for all workload conditions were found until 60 minutes into task performance, but after that time, amplitudes stayed relatively level. Note the high standard errors for all workload conditions. Correlation between onset amplitude and peak amplitude was highly significant ($R^2=0.834$, $p<0.001$) as shown in Figure 6.16.
Figure 6.14 Onset amplitude during three hours of task performance
(each bar represents the respective standard error)
Figure 6.15 Peak amplitude during three hours of task performance
(each bar represents the respective standard error)
Figure 6.16 Correlation between onset amplitude and peak amplitude

The repeated measures analysis of variance on onset amplitude and peak latency were conducted to investigate the strength of association between the nerve conduction measures and subject, force, repetition, and time, and the results are shown in Table 6.14, and Table 6.15, respectively. Significant main effects for subject (F=67.94, p<0.001), force (F=9.66, p<0.001), repetition (F=20.18, p<0.001), and time (F=8.85, p<0.001) were found. The repeated measures analysis of variance on peak amplitude produced similar statistical findings with onset amplitude except for a significant, though weak, force × repetition interaction effect (F=4.77, p<0.05).
Similar to latency results, the amplitude change in low force conditions were significantly higher than those in high force conditions, and the amplitude change in low repetition conditions were significantly greater than those in high repetition conditions, though the effects were weaker than in latency change. These were also unexpected results and similar to the peak latency, may also be explained by the complicated relationships between workload, heat gain, air flow to the hand, with changes in skin temperature affecting nerve conduction measures.

Table 6.14 ANOVA for onset amplitude

<table>
<thead>
<tr>
<th>Source</th>
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<th>F</th>
<th>P</th>
</tr>
</thead>
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<td>SUBJECT</td>
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<td>55834.3</td>
<td>3988.2</td>
<td>67.94</td>
<td>0.000 *</td>
</tr>
<tr>
<td>FORCE</td>
<td>1</td>
<td>705.4</td>
<td>705.4</td>
<td>12.02</td>
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</tr>
<tr>
<td>REPETITION</td>
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<td>1184.6</td>
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<td>20.18</td>
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</tr>
<tr>
<td>TIME</td>
<td>9</td>
<td>4673.5</td>
<td>519.3</td>
<td>8.85</td>
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</tr>
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<td>FORCE*REPETITION</td>
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</tr>
<tr>
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Table 6.15 ANOVA for peak amplitude

<table>
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<th>Source</th>
<th>DF</th>
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<td>6186.6</td>
<td>37.96</td>
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</tr>
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<td>TIME</td>
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<td>1878.2</td>
<td>11.52</td>
<td>0.000 *</td>
</tr>
<tr>
<td>FORCE*REPETITION</td>
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<td>777.5</td>
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<td>4.77</td>
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<tr>
<td>FORCE*TIME</td>
<td>9</td>
<td>543.4</td>
<td>60.4</td>
<td>0.37</td>
<td>0.949</td>
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<tr>
<td>REPETITION*TIME</td>
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<td>937.6</td>
<td>104.2</td>
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<tr>
<td>FORCE<em>REPETITION</em>TIME</td>
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<td>88.1</td>
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</table>
Post-hoc paired comparisons on time (i.e. duration of exposure) were performed separately for each workload condition using Tukey Simultaneous Tests to further explore where the onset amplitude and peak amplitude deviated from the initial baseline measure (i.e. time = 0). The results are presented in Table 6.16. Onset amplitude results for LOF.LOR condition indicated that the amplitudes at time = 60 and time = 180 were significantly different from the initial baseline measure, but the amplitudes between time = 20 and time = 180 were not statistically differentiated. For HIF.LOR condition, amplitudes at time = 40 and between time = 80 and 180 were significantly greater than initial amplitude (time = 0), while for LOF.HIF condition amplitudes after time = 60 were significantly greater than the initial baseline measure. But, the amplitude for HIF.HIR was not statistically different during the three hours of task performance.

Post-hoc paired comparisons on time (i.e. duration of exposure) for peak amplitude also produced results very similar to onset amplitude (see Table 6.17).
### Table 6.16 Pairwise comparison for time on onset amplitude

<table>
<thead>
<tr>
<th>Workload</th>
<th>Time (min)</th>
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<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>100</th>
<th>120</th>
<th>140</th>
<th>160</th>
<th>180</th>
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<tbody>
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<td>LOF.LOR</td>
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<tr>
<td>HIF.LOR</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOF.HIR</td>
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<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HIF.HIR</td>
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Note: Underlining (thin or thick) pairs mean ‘not significantly different’, and thicker lines represent “significant differences” to thin lines.

### Table 6.17 Pairwise comparison for time on peak amplitude

<table>
<thead>
<tr>
<th>Workload</th>
<th>Time (min)</th>
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<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
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<td>LOF.LOR</td>
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<td>HIF.LOR</td>
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<tr>
<td>LOF.HIR</td>
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<tr>
<td>HIF.HIR</td>
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</tbody>
</table>

Note: Underlining (thin or thick) pairs mean ‘not significantly different’, and thicker lines represent “significant differences” to thin lines.
6.3 Median Motor Nerve Conduction Change after Three Hours Workload

6.3.1 Onset Latency

The median motor nerve conduction measures were measured immediately before the start of the task (time = 0) and at the end of the task (time = 180). The results of median motor nerve onset latency seen in Figure 6.17 indicated that mean initial onset latency at time = 0 across participants were similar across workload conditions. However, exposure to wrist workload produced a noticeable difference in motor nerve onset latency. The overall pattern was compared with the results of median sensory nerve onset latency.

The repeated measures analysis of variance on motor nerve onset latency was conducted to investigate the strength of association between the nerve conduction measures and subject, force, repetition, and time. Significant main effects on onset latency were detected for subject ($F_{14,98}=12.62$, $p<0.001$), force ($F_{1,98}=19.80$, $p<0.001$), and time ($F_{1,98}=45.89$, $p<0.001$). There was also a significant force × time interaction effect ($F_{1,98}=14.91$, $p<0.01$). Interestingly, however, the repetition was not significant ($F_{1,98}=3.53$, $p=0.063$) on motor nerve onset latency. Thus, post-hoc paired comparisons on force indicated that the latency change in low force conditions were significantly greater than those in high force conditions. This was also unexpected. It is therefore
postulated that there were interactions between workload, heat gain, air flow to the hand, skin temperature and nerve conduction measure.

<table>
<thead>
<tr>
<th>Onset Latency (msec)</th>
<th>Time (min)</th>
<th>Significance</th>
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<td>HIF.LOR</td>
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<td>3.94</td>
</tr>
<tr>
<td>LOF.HIR</td>
<td>3.65</td>
<td>4.26</td>
</tr>
<tr>
<td>HIF.HIR</td>
<td>3.64</td>
<td>3.71</td>
</tr>
</tbody>
</table>

Figure 6.17 Motor nerve onset latency during task performance
(each bar represents the respective standard error)

6.3.2 Onset Amplitude

The results of median motor nerve onset amplitude during task performance were calculated across participants for each condition, and are shown in Figure 6.18. Interestingly, unlike results of sensory nerve amplitude, no significant changes in
amplitude were detected for workload conditions. The repeated measures analysis of variance on onset amplitude confirmed this explanation where all main effects and interaction effect were not significant, except of significant main effect for subject (F_{14,98}=40.68, p<0.001). This results were in accord with the study of Rutkove (2001) who reported that temperature-related effects on motor nerve amplitude tend to be more modest than these observed in sensory nerve amplitude studies.

![Figure 6.18](image)

**Figure 6.18** Motor nerve onset amplitude during task performance (each bar represents the respective standard error)
6.4 Skin Temperature Change during Three Hours Workload

6.4.1 Skin Temperature

Since the correlation between median nerve function and skin temperature is widely reported, the skin temperature was carefully monitored and recorded on dorsum of hand (metacarpal bones of index finger). A minimum skin temperature of 31°C was ensured by using heated water or radiator before the start of experimentation if necessary. The skin temperature was measured immediately before and every 20 minutes thereafter corresponding to each nerve conduction measurement. The results of skin temperature measurements during task performance were calculated across participants for each condition, and are shown in Figure 6.19. The results indicated that mean initial skin temperature measures at time = 0 across participants were similar across workload conditions, however exposure to wrist workload produced a noticeable difference in skin temperature measures. The general pattern of the skin temperature graphs was similar to the reverse graph of peak latency suggesting a possible correlation between measures. This observation is highly suggestive of a possible association between cooling of the hand and sensory median nerve performance. Evidence in the literature performing to ischemic involvement in the etiology of carpal tunnel syndrome supports these observations.
Figure 6.19  Skin temperature change during three hours of task performance

(each bar represents the respective standard error)
Table 6.18 shows the repeated measures analysis of variance on skin temperature for subject, force, repetition, and time. Significant main effects on skin temperature were detected for subject (F=33.34, p<0.001), force (F=80.30, p<0.001), repetition (F=59.93, p<0.001), and time (F=17.24, p<0.001). There were also significant force × repetition (p<0.05, F=5.99) and force × time (p<0.05, F=1.92) interaction effects.

Table 6.18 ANOVA for skin temperature

<table>
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<tr>
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<td>188.720</td>
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<td>TIME</td>
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<tr>
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6.4.2 Correlation of Skin Temperature and Sensory Nerve Conduction

In general, as the skin temperature decreased, the nerve conduction action potential showed a prolonged latency and increased amplitude. Correlation analyses were performed between skin temperature and nerve conduction measures using Pearson correlation technique at a significant level of $\alpha = 0.05$ across participants, force, repetition, and time. Figure 6.20 and Figure 6.21 show the peak latency and peak
amplitude, respectively, as a function of skin temperature for 15 subjects performing task during three hours. The least squares linear regression equations and its R-squares are also presented for each relationship.

Highly significant correlation ($R^2 = 0.7365, p<0.001$) between the peak latency and skin temperature was detected. This means that the results of prolonged peak latency obtained during the three hours of task performance (see section 6.2.1) might be influenced by skin temperature changes. There was also a significant relationship ($R^2 = 0.2842, p<0.001$) between the onset amplitude and skin temperature. These findings are highly consistent with those in the studies of Rutkove (2001), Burke et al. (1999a), Asworth et al. (1998), Rutkove et al. (1997), Letz and Gerr (1994), Baysal et al. (1993), Lee et al. (1993) and Tashjian et al. (1987). They reported that as the skin temperature decreases, the nerve conduction action potential recorded from a nerve demonstrates an increased amplitude and prolonged latency.

On the other hand, the effect of temperature on sensory nerve action potentials is largely due to neuronal changes in $\text{Na}^+$ (sodium) channel function. A decrease in temperature slows down both the opening and closing of the $\text{Na}^+$ channel, with the closing being more affected than the opening. This phenomenon has several effects. First, the slower depolarization translates into a prolonged latency for the axon. Second, as additional ions move into the cell during the prolonged opening, a larger depolarization occurs and the response amplitude increases.
Figure 6.20 Correlation between skin temperature and peak latency

Figure 6.21 Correlation between skin temperature and peak amplitude
6.5 Median Sensory Nerve Conduction after Skin Temperature Correction

6.5.1 Temperature-corrected Peak Latency

As seen in previous section, the skin temperature had significant correlations with nerve conduction measures. Nerve impulses conduct faster at high skin temperature and slower at low skin temperature. Among several studies investigating the temperature effects on nerve conduction measures, Lee et al. (1993) reported that the antidromic median sensory nerve latency was delayed by 0.1 msec/degree with cooling. Using same measurement techniques with this study, they measured sensory nerve peak latency by stimulating over median nerve on wrist and recording with ring electrodes over index finger 14 cm distal to stimulating electrodes. Therefore, their study results were used as a correction factor to adjust the temperature effects on sensory nerve peak latency.

Figure 6.22 shows the results of median sensory nerve peak latency after skin temperature correction. Even though the slopes for workload conditions were adjusted, the results indicated that skin temperature-corrected peak latency produced results similar to previous peak latency. Temperature-corrected peak latencies for LOF.LOR, HIF.LOR, and LOF.HIR conditions increased during the three hours of task performance, while peak latency for HIF.HIR condition slightly decreased.
Figure 6.22 Sensory nerve peak latency after skin temperature correction
(each bar represents the respective standard error)
The repeated measures analysis of variance on temperature-corrected peak latency also produced very similar results of significant main effects and interaction effect with previous peak latency (refer to Table 6.11). Significant main effects on peak latency were found for subject ($F_{14,546}=21.74$, $p<0.001$), force ($F_{1,546}=72.80$, $p<0.001$), repetition ($F_{1,546}=46.73$, $p<0.001$), and time ($F_{9,546}=4.69$, $p<0.001$). There was also a significant force $\times$ time interaction effect ($F_{9,546}=1.90$, $p<0.05$). However, the results still indicated that latency change in low force conditions were significantly greater than those in high force conditions, and the latency change in low repetition conditions were significantly larger than those in high repetition conditions. These results may be partly explained by the relationships between sensory nerve peak latency and workload variables such as the total range of motions and cumulative time as will be discussed in greater detail later.

Post-hoc paired comparisons on time (i.e., duration of exposure), shown in Table 6.19 indicated that significant ($p<0.05$) change in temperature-corrected peak latency in the LOF.LOR condition occurred 120 minutes into task performance. For LOF.HIR conditions, significant change in temperature-corrected peak latency was first noted after 160 minutes, while temperature-corrected peak latencies for HIF.LOR and HIF.HIR conditions did not change over the three hours of task performance.

These results may indicate a temporal focal demyelination of median nerve due to the recurrent compression to carpal tunnel, since the temperature-corrected peak latency still showed a prolonged distal latency response, whereas for individual myelinated nerve fibers, focal demyelination caused a slowing in conduction.
Table 6.19 Pairwise comparison for time on temperature-corrected peak latency

<table>
<thead>
<tr>
<th>Workload</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>LOF.LOR</td>
<td></td>
</tr>
<tr>
<td>HIF.LOR</td>
<td></td>
</tr>
<tr>
<td>LOF.HIR</td>
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<tr>
<td>HIF.HIR</td>
<td></td>
</tr>
</tbody>
</table>

Note: Underlining (thin or thick) pairs mean ‘not significantly different’, and thicker lines represent “significant differences” to thin lines.

6.5.2 Temperature-corrected Peak Amplitude

Among several studies investigating the temperature effect on sensory nerve peak amplitude, Tashjian et al. (1987) reported that the antidromic median sensory nerve amplitude was found to increase with upper extremity cooling by 3.5 µV per degree. The results of the temperature-corrected peak amplitude according to Tashjian et al. (1987) are presented in Figure 6.23. The results indicated that for all workload conditions skin temperature-corrected peak amplitudes produced overall slight increases until 60 minutes into task performance. After that the peak amplitudes showed decreased trends. There were high standard errors for all workload conditions. Thus, little differences between workload conditions were found on temperature-corrected peak amplitude.
Figure 6.23 Sensory nerve peak amplitude after skin temperature correction (each bar represents the respective standard error)
The repeated measures analysis of variance on temperature-corrected peak amplitude also produced similar results with previous peak amplitude (refer to Table 6.15). Significant main effects on the temperature-corrected peak amplitude were detected for subject \( (F_{14,546}=95.22, p<0.001) \), repetition \( (F_{1,546}=11.64, p=0.001) \), and time \( (F_{9,546}=4.62, p<0.001) \). However, force \( (F_{14,546}=3.00, p=0.084) \) had no effect on temperature-corrected amplitude, and even the repetition had a very weak relationship with the peak amplitude. There were no significant interaction effects.

Post-hoc paired comparisons on time (i.e. duration of exposure) shown in Table 6.20 indicated that significant \( (p<0.05) \) changes in temperature-corrected amplitude were found only for HIF.LOR, and HIF.HIR conditions. This was largely because the temperature-corrected amplitude had high variance which might make it difficult to find significant differences.

On the other hand, the temperature-corrected peak amplitude results may indicate that the exposure to workload stressor during the three hours of task performance might not have caused the axon-loss lesions to the median nerve, since diminution of sensory nerve action potential amplitudes is the most sensitive indicator of axon-loss lesions.
Table 6.20 Pairwise comparison for time on temperature-corrected peak amplitude

<table>
<thead>
<tr>
<th>Workload</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 20 40 60 80 100 120 140 160 180</td>
</tr>
<tr>
<td>LOF.LOR</td>
<td></td>
</tr>
<tr>
<td>HIF.LOR</td>
<td></td>
</tr>
<tr>
<td>LOF.HIR</td>
<td></td>
</tr>
<tr>
<td>HIF.HIR</td>
<td></td>
</tr>
</tbody>
</table>

Note: Underlining (thin or thick) pairs mean ‘not significantly different’, and thicker lines represent “significant differences” to thin lines

6.6 Regression Analysis between Sensory Nerve Conduction and Time

Since onset latency might be mismeasured due to signal artifact and a false onset point, the reliability of onset latency as an objective measure of median nerve function is questionable. Also amplitude might be influenced by several external as well as internal variables, including electrode placement, skin conductivity, sweating, and stimulus level. Since peak latency is able to accurately identify the point of highest amplitude along the waveform, it, from now on, will be used as the only reliable nerve conduction measure. On the other hand, even though the change in skin temperature would likely be due to imposed workload stressors, both peak latency and temperature-corrected peak latency will be investigated in all subsequent analyses.
6.6.1 Sensory Nerve Peak Latency and Time

Since a highly significant effect of time (i.e. duration of exposure to workload) on sensory nerve peak latency was detected, regression analysis was performed between sensory nerve peak latency and time using stepwise regression method across participants on each workload condition. Stepwise regression method removes and adds variables to the regression model for the purpose of identifying a useful subset of the predictors. These variables are removed if their p-values are greater than the Alpha to enter value. In this study, $\alpha=0.25$ were used for “to enter” and “to remove”. The results are presented in Figure 6.34 and Table 6.21.

Among four workload conditions, peak latencies of LOF.LOR and LOF.HIR conditions went beyond the empirical upper limit of normal range (mean = 3.16 msec, limit of normal = 3.5 msec (+2\(\sigma\)); Jackson and Clifford, 1989) during the three hours of task performance. Based on the limit of normal peak latency and the regression equation in Table 6.21, the exposure time (duration of exposure to workload) required to produce clinical evidence of carpal tunnel syndrome was calculated. For LOF.LOR condition, the time was 67.1 minutes, while for LOF.HIF condition, the time was 163 minutes. Thus, the figure also includes the 1\(\sigma\) (3.32 msec) and 3\(\sigma\) (3.64 msec) limits of normal for sensory peak latency (Jackson and Clifford, 1989).
Figure 6.24 Regression between peak latency and time

Table 6.21 Stepwise regression between peak latency and time

<table>
<thead>
<tr>
<th>Peak Latency of</th>
<th>Constant</th>
<th>Polynomial Variables of Time</th>
<th>R-sq (%)</th>
<th>P value</th>
<th>Time to produce CTS (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>TIME</td>
<td>TIME²</td>
<td>TIME³</td>
<td>TIME⁴</td>
</tr>
<tr>
<td>LOF.LOR</td>
<td>= 3.131</td>
<td>0.00676</td>
<td>-1.88E-05</td>
<td>99.7</td>
<td>0.000</td>
</tr>
<tr>
<td>HIF.LOR</td>
<td>= 3.095</td>
<td>0.00368</td>
<td>-6.39E-08</td>
<td>98.0</td>
<td>0.000</td>
</tr>
<tr>
<td>LOF.HIR</td>
<td>= 3.052</td>
<td>0.00659</td>
<td>-2.95E-05</td>
<td>1.37E-12</td>
<td>99.1</td>
</tr>
<tr>
<td>HIF.HIR</td>
<td>= 3.047</td>
<td>0.00069</td>
<td>-5.08E-11</td>
<td>70.3</td>
<td>0.014</td>
</tr>
</tbody>
</table>
6.6.2 Temperature-corrected Sensory Nerve Peak Latency and Time

Even though change in skin temperature would likely be due to imposed workload stressors, the regression analysis between the temperature-corrected peak latency and time (duration of exposure to workload) was also studied, if it is assumed that the skin temperature remains fairly level during a three-hour task.

The regression analyses using same stepwise regression method on each workload condition are presented in Figure 6.25 and Table 6.22. The results indicated that for all workload conditions, the temperature-corrected peak latencies did not attained the empirical lower limit of normal range (mean = 3.16 msec, limit of normal = 3.5 msec; Jackson and Clifford, 1989) within three hours of task performance. However the results of increased peak latency mean that the workload conditions of LOF.LOR, HIF.LOR, and LOF.HIR can cause some cumulative effects on wrist if such conditions continue repeatedly for a long period of time.
Figure 6.25  Regression between temperature-corrected peak latency and time

Table 6.22  Stepwise regression between temperature-corrected peak latency and time

<table>
<thead>
<tr>
<th>Peak Latency of</th>
<th>Constant</th>
<th>Polynomial Variables of Time</th>
<th>R-sq (%)</th>
<th>P value</th>
<th>Time to produce CTS (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>TIME</td>
<td>TIME^2</td>
<td>TIME^5</td>
<td></td>
</tr>
<tr>
<td>LOF.LOR</td>
<td>3.098</td>
<td>0.00337</td>
<td>-9.81E-06</td>
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<td>91.0</td>
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<tr>
<td>HIF.LOR</td>
<td>3.107</td>
<td>-0.00003</td>
<td>1.05E-05</td>
<td>-1.43E-12</td>
<td>89.7</td>
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<tr>
<td>LOF.HIR</td>
<td>3.100</td>
<td>0.00146</td>
<td>-3.38E-06</td>
<td></td>
<td>94.9</td>
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<tr>
<td>HIF.HIR</td>
<td>3.076</td>
<td>0.00008</td>
<td>3.26E-13</td>
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<td>67.0</td>
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</table>
6.7 Sensory Nerve Peak Latency Shift following Three Hours Performance

The median nerve sensory peak latency and temperature-corrected peak latency shifts between time = 0 and time = 180 were computed to illustrate the effect of time (i.e. duration of exposure to workload) on each workload condition. It assumed that the peak latency measurements follow normal distribution, therefore the measurements across participants on each workload condition convert into normal probability density function.

The mean peak latency and temperature-corrected peak latency shifts for each condition are presented in Figure 6.26–Figure 6.33. The empirical upper limits of normal for sensory peak latency (3.5 msec (2σ); Jackson and Clifford, 1989) and the 1σ (3.32 msec) and 3σ (3.64 msec) limits are indicated on figures, clearly showing that the three hours of task performance produced the clinical evidence of carpal tunnel syndrome, while the initial peak latency probability distribution at time = 0 was located below the upper limit of normal. Also, the probability that peak latency or temperature-corrected peak latency after the three hours of task performance are greater than 3.5 msec were calculated and presented on figures. Specially, for LOF.LOR condition, the probability that the peak latency at time=180 is greater than 3.5 msec was 0.6773. This means that 67.73 percent of people might have temporary peak latency increases beyond 3.5 msec when they work in the low force and low repetition condition. On the other hand, assuming fairly even skin temperatures during three hours task, the probability fell to 0.3289, which is, however, still very high. The mean and standard deviation, and the probability for each workload condition were summarized in Table 6.23.
Figure 6.26  Peak latency shift in LOF.LOR condition

Figure 6.27  Temperature-corrected peak latency shift in LOF.LOR condition
Figure 6.28  Peak latency shift in HIF.LOR condition

Figure 6.29  Temperature-corrected peak latency shift in HIF.LOR condition
Figure 6.30 Peak latency shift in LOF.HIR condition

Figure 6.31 Temperature-corrected peak latency shift in LOF.HIR condition
Figure 6.32 Peak latency shift in HIF.HIR condition

Figure 6.33 Temperature-corrected peak latency shift in HIF.HIR condition
Table 6.23  Summary of peak latency shift

<table>
<thead>
<tr>
<th>Workload Conditions</th>
<th>Peak Latency</th>
<th>Temperature-corrected Peak Latency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time =0</td>
<td>Time =180</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>SD</td>
</tr>
<tr>
<td>LOF.LOR</td>
<td>3.13</td>
<td>0.1494</td>
</tr>
<tr>
<td>HIF.LOR</td>
<td>3.11</td>
<td>0.0763</td>
</tr>
<tr>
<td>LOF.HIR</td>
<td>3.06</td>
<td>0.1324</td>
</tr>
<tr>
<td>HIF.HIR</td>
<td>3.06</td>
<td>0.1002</td>
</tr>
</tbody>
</table>

Thus, the low probability for HIF.HIR condition should be explained by the relationships between workload, heat gain, air flow to the hand, with changes in skin temperature affecting nerve conduction measures.

6.8  Associations between Sensory Nerve Conduction and Workload Variables

6.8.1  Correlation Analysis between Sensory Nerve Peak Latency and Workloads

Since workload variables were calculated as composite workload measures for each participant, the median nerve sensory peak latency difference between time = 0 and time = 180 were calculated as dependent variable on each workload condition for each
participant. Only peak latency and temperature-corrected peak latency were used to compare the relationships with workload variables.

Correlation analyses were performed between sensory nerve peak latency change and workload variables using Pearson’s technique (at $\alpha=0.05$) across workload conditions and participants. Thus, the correlation analyses between peak latency and cumulative time, and cumulative angle-time exposure were performed with four different thresholds of wrist angle on F/E angle > 30°, F/E angle > 35°, F/E angle > 40°, F/E angle > 45° to find out the best relationship between them. Table 6.24 listed the correlation results. Findings of the correlation analyses on peak latency were highly significant for maximum wrist flexion angle, maximum wrist range of motion, cumulative time variables (F/E angle > 30°, 35°, and 40°), and all cumulative angle-time exposure variables (F/E angle > 30°, 35°, 40°, and 45°). The strongest correlation was present between maximum wrist range of motion and sensory nerve peak latency ($r=0.4648$, $p<0.001$), where sensory nerve peak latency appears to increase as the maximum wrist range of motion increases. Among relationships between peak latency and the four cumulative time variables, the strongest correlation was found between cumulative time of F/E angle > 30° and sensory nerve peak latency change ($r=0.3715$, $p=0.005$) where sensory nerve peak latency increased as the cumulative time of F/E angle > 30° increased. One the other hand, the correlation between cumulative angle-time exposure of
F/E angle > 30° and peak latency was largest (r=0.3450, p=0.009) among the relationships between peak latency and four cumulative angle-time exposure variables.

For temperature-corrected peak latency, correlation analyses found results similar to peak latency. Correlation analyses revealed significant results for maximum wrist flexion angle, maximum wrist range of motion, mean angular velocity, cumulative time variables (F/E angle > 30°, and 35°), and all cumulative angle-time exposure variable (F/E angle > 30°, 35°, 40°, and 45°). Among relationships between temperature corrected peak latency and cumulative time variables, the strongest correlation was also detected between cumulative time of F/E angle>30° and temperature corrected peak latency (r=0.3098, p=0.022).
Table 6.24 Correlation analysis between peak latency and workload variables

<table>
<thead>
<tr>
<th>Workload Variables</th>
<th>Nerve Conduction Variables</th>
<th></th>
<th></th>
<th>Nerve Conduction Variables</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak Latency</td>
<td>r</td>
<td>p</td>
<td>Direction</td>
<td>r</td>
<td>p</td>
</tr>
<tr>
<td>Mean Pinch Force</td>
<td>-0.1265</td>
<td>0.512</td>
<td>Negative</td>
<td>-0.1049</td>
<td>0.578</td>
<td>Negative</td>
</tr>
<tr>
<td>Maximum Pinch Force</td>
<td>0.1020</td>
<td>0.605</td>
<td>Positive</td>
<td>0.3302</td>
<td>0.100</td>
<td>Positive</td>
</tr>
<tr>
<td>Mean F/E Angle</td>
<td>0.1673</td>
<td>0.214</td>
<td>Positive</td>
<td>-0.2121</td>
<td>0.126</td>
<td>Negative</td>
</tr>
<tr>
<td>Maximum Wrist Flexion Angle</td>
<td>-0.4231</td>
<td>0.002</td>
<td>Negative</td>
<td>-0.4037</td>
<td>0.003</td>
<td>Negative</td>
</tr>
<tr>
<td>Maximum Wrist Extension Angle</td>
<td>0.1975</td>
<td>0.129</td>
<td>Positive</td>
<td>0.1581</td>
<td>0.230</td>
<td>Positive</td>
</tr>
<tr>
<td>Maximum Wrist Range of Motion</td>
<td>0.4648</td>
<td>0.000</td>
<td>Positive</td>
<td>0.4701</td>
<td>0.000</td>
<td>Positive</td>
</tr>
<tr>
<td>Mean Angular Velocity</td>
<td>0.2049</td>
<td>0.163</td>
<td>Positive</td>
<td>0.2983</td>
<td>0.027</td>
<td>Positive</td>
</tr>
<tr>
<td>Maximum Angular Velocity</td>
<td>0.0320</td>
<td>0.814</td>
<td>Positive</td>
<td>0.1449</td>
<td>0.297</td>
<td>Positive</td>
</tr>
<tr>
<td>Mean Angular Acceleration</td>
<td>0.0680</td>
<td>0.649</td>
<td>Positive</td>
<td>0.1612</td>
<td>0.242</td>
<td>Positive</td>
</tr>
<tr>
<td>Maximum Angular Acceleration</td>
<td>0.0330</td>
<td>0.810</td>
<td>Positive</td>
<td>0.1225</td>
<td>0.361</td>
<td>Positive</td>
</tr>
<tr>
<td>Cumulative Time F/E Angle &gt; 30</td>
<td>0.3715</td>
<td>0.005</td>
<td>Positive</td>
<td>0.3098</td>
<td>0.022</td>
<td>Positive</td>
</tr>
<tr>
<td>Cumulative Time F/E Angle &gt; 35</td>
<td>0.3376</td>
<td>0.012</td>
<td>Positive</td>
<td>0.2828</td>
<td>0.047</td>
<td>Positive</td>
</tr>
<tr>
<td>Cumulative Time F/E Angle &gt; 40</td>
<td>0.2720</td>
<td>0.044</td>
<td>Positive</td>
<td>0.2387</td>
<td>0.094</td>
<td>Positive</td>
</tr>
<tr>
<td>Cumulative Time F/E Angle &gt; 45</td>
<td>0.2345</td>
<td>0.085</td>
<td>Positive</td>
<td>0.2550</td>
<td>0.077</td>
<td>Positive</td>
</tr>
<tr>
<td>Cumulative Angle-time Exposure F/E Angle &gt; 30</td>
<td>0.3450</td>
<td>0.009</td>
<td>Positive</td>
<td>0.3479</td>
<td>0.012</td>
<td>Positive</td>
</tr>
<tr>
<td>Cumulative Angle-time Exposure F/E Angle &gt; 35</td>
<td>0.3332</td>
<td>0.012</td>
<td>Positive</td>
<td>0.3435</td>
<td>0.013</td>
<td>Positive</td>
</tr>
<tr>
<td>Cumulative Angle-time Exposure F/E Angle &gt; 40</td>
<td>0.3225</td>
<td>0.015</td>
<td>Positive</td>
<td>0.3406</td>
<td>0.013</td>
<td>Positive</td>
</tr>
<tr>
<td>Cumulative Angle-time Exposure F/E Angle &gt; 45</td>
<td>0.3347</td>
<td>0.013</td>
<td>Positive</td>
<td>0.3406</td>
<td>0.013</td>
<td>Positive</td>
</tr>
</tbody>
</table>

Note: bolded denotes significance at $\alpha = 0.05$
6.8.2 Association between Peak Latency and Maximum Flexion Angle

Since a highly significant association between peak latency and maximum wrist flexion angle was detected, linear regression analysis was performed to further explore the relationship between them (see Figure 6.34 and Table 6.25). A significant relationship was found between maximum wrist flexion angle and sensory nerve peak latency ($R^2 = 17.9\%$, $p=0.002$), where sensory peak latency increased by 0.01 msec for each 1 degree decrease in the maximum flexion angle during the three hours of task performance. Given an empirical upper limit of normal peak latency change of 0.34 msec (mean = 3.16 msec, limit of normal = 3.5 msec; Jackson and Clifford, 1989) and based on regression analysis, the threshold wrist flexion angle that may impede sensory median nerve function at the level of clinical evidence for carpal tunnel syndrome was calculated to be -64.1 degrees.

Linear regression analysis between temperature-corrected peak latency and maximum wrist flexion angle is presented in Figure 6.35 and Table 6.26. The maximum allowable wrist flexion angle on temperature-corrected peak latency change was -107.3 degrees.
Figure 6.34  Association between peak latency and maximum flexion angle

Table 6.25  Regression analysis between peak latency and maximum flexion angle

The regression equation is

\[
\text{Peak Latency Change} = -0.344161 - 0.0106823 \times \text{Maximum Flexion Angle}
\]

\[S = 0.296423 \quad \text{R-Sq} = 17.9\%
\]

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
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<td>Regression</td>
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<td>0.96070</td>
<td>0.960704</td>
<td>10.9337</td>
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<td>Total</td>
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<td>5.35403</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 6.35  Association between temperature-corrected peak latency and maximum flexion angle

Table 6.26  Regression analysis between temperature-corrected peak latency and maximum flexion angle

The regression equation is

\[
\text{TC Peak Latency Change} = -0.291 - 0.00588 \times \text{Maximum Flexion Angle}
\]

\[
S = 0.1784 \quad \text{R-Sq} = 16.3\% \quad \text{R-Sq(adj)} = 14.6\%
\]

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
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<th>MS</th>
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<th>P</th>
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<td>Total</td>
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<td></td>
<td></td>
<td></td>
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</table>
6.8.3 Association between Peak Latency and Maximum Range of Motions

Figure 6.36 and Table 6.27 show linear regression analysis between peak latency and maximum wrist range of motion. Sensory nerve peak latency had a very strong relationship with maximum wrist range of motion ($R^2 = 21.6\%$, $p < 0.001$), where sensory peak latency increased by 0.01155 msec for each 1 degree increase in the maximum wrist range of motion during the three hours of task performance.

Given an empirical low limit of normal peak latency change of 0.34 msec and based on regression analysis, the maximum allowable range of motion on peak latency change was 133.2 degrees, while that on temperature-corrected peak latency was 162.8 degrees. Linear regression analysis between temperature corrected peak latency and maximum wrist range of motion was shown in Figure 6.37 and Table 6.28.
Figure 6.36  Association between peak latency and maximum range of motion

Table 6.27  Regression analysis between peak latency and maximum range of motion

The regression equation is

\[
\text{Peak Latency Change} = -1.198 + 0.01155 \times \text{Maximum Range of Motion}
\]

\[
S = 0.321011 \quad R^2 = 21.6\%
\]

Analysis of Variance

<table>
<thead>
<tr>
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<th>SS</th>
<th>MS</th>
<th>F</th>
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</thead>
<tbody>
<tr>
<td>Regression</td>
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<td>Error</td>
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<td>Total</td>
<td>54</td>
<td>6.96484</td>
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</tr>
</tbody>
</table>
Figure 6.37 Association between temperature-corrected peak latency and maximum range of motion

Table 6.28 Regression analysis between temperature-corrected peak latency and maximum range of motion

The regression equation is

\[ \text{TC Peak Latency Change} = -0.839 + 0.00724 \times \text{Maximum Range of Motion} \]

\[ S = 0.2163 \quad \text{R-Sq} = 22.1\% \quad \text{R-Sq(adj)} = 20.7\% \]

Analysis of Variance

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<th>MS</th>
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<th>P</th>
</tr>
</thead>
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<td>3.30303</td>
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</table>
6.8.4 Association between Peak Latency and Mean Angular Velocity

Since a significant association between temperature-corrected peak latency and mean angular velocity was found, linear regression analysis was performed. The results shown in Figure 6.38 and Table 6.29, showed a significant positive relationship between mean angular velocity and temperature-corrected peak latency ($R^2=8.9\%$, $p=0.027$). Sensory peak latency increased by 0.00145 msec for each 1 degree/sec increase in the mean angular velocity during the three hours of task performance. Given the same empirical low limit of normal peak latency change of 0.34 msec and based on regression analysis, the maximum allowable mean angular velocity was 335.9 degree/sec.
Figure 6.38  Association between temperature-corrected peak latency and mean angular velocity

Table 6.29  Regression analysis between temperature-corrected peak latency and mean angular velocity

The regression equation is

\[
\text{TC Peak Latency Change} = -0.147 + 0.00145 \times \text{Mean Angular Velocity}
\]

\[S = 0.2020 \quad R-Sq = 8.9\% \quad R-Sq(adj) = 7.2\%\]

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
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<th>SS</th>
<th>MS</th>
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<th>P</th>
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</thead>
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<td>0.21174</td>
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<td>0.027</td>
</tr>
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<td>Total</td>
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<td>2.37493</td>
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</table>
6.8.5 Association between Peak Latency and Cumulative Time

The highest significant association was found between peak latency and cumulative exposure time at F/E angle > 30° among the various cumulative time variables (F/E angle > 30°, 35°, 40°, and 45°), linear regression analysis was performed to further explore the relationship (see Figure 6.39 and Table 6.30). Median sensory nerve peak latency change had a highly significant relationship with cumulative exposure time of F/E angle > 30° ($R^2=13.8\%$, $p=0.005$), where sensory peak latency increased by 0.0000777 msec for each 1 second (0.04662 msec per 10 minutes) increase in the cumulative exposure time of F/E angle > 30° during the three hours of task performance. This relationship may be the most important finding of this study, because the cumulative exposure time includes the time factor as well as wrist angular deviation factor during task performance.

Given the same empirical low limit of normal peak latency change of 0.34 msec and based on regression analysis, the maximum allowable cumulative exposure time of F/E angle > 30° on peak latency was 124.6 minutes, while the time on temperature-corrected peak latency extended to 222.6 minutes. Figure 6.40 and Table 6.31 show linear regression analysis between cumulative time of F/E angle > 30° and temperature-corrected peak latency change.
Figure 6.39  Association between peak latency and cumulative time of F/E > 30°

Table 6.30  Regression analysis between peak latency and cumulative time of F/E > 30°

The regression equation is

\[
\text{Peak Latency Change} = -0.241021 + 0.0000777 \times \text{Cumulative Time of F/E Angle > 30 degree (sec)}
\]

\[ S = 0.309170 \quad \text{R-Sq} = 13.8 \% \]

Analysis of Variance

<table>
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<tr>
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<th>MS</th>
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<td>0.808676</td>
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<td>5.06606</td>
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<td>5.87473</td>
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</table>
Figure 6.40  Association between temperature-corrected peak latency and cumulative time of F/E > 30°

Table 6.31  Regression analysis between temperature-corrected peak latency and cumulative time of F/E > 30°

The regression equation is

\[ TC \text{ Peak Latency Change} = -0.221 + 0.000042 \times \text{Cumulative Time of F/E Angle > 30°} \]

\[ S = 0.2041 \quad R^2 = 9.6\% \quad R^2(\text{adj}) = 7.9\% \]

Analysis of Variance

<table>
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<tr>
<th>Source</th>
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<td>2.44125</td>
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6.8.6 Association between Peak Latency and Cumulative Angle-time Exposure

Like the relationship between peak latency and cumulative time, the highest significant association was found between peak latency and cumulative angle-time exposure at F/E angle > 30° among the various cumulative angle-time exposure variables (F/E angle > 30°, 35°, 40°, and 45°). Therefore, linear regression analysis between them was performed, and the results are shown in Figure 6.41 and Table 6.32. A significant relationship was detected between cumulative angle-time exposure of F/E angle > 30° and sensory nerve peak latency change (R²=11.9%, p=0.009), where sensory peak latency increased by 0.0000022 msec for each 1 degree*second (0.0396 msec per 300 degree*minute) increase in the cumulative angle-time exposure of F/E angle > 30° during the three hours of task performance. Given the same empirical low limit of normal peak latency change of 0.34 msec and based on regression analysis, the maximum allowable cumulative angle-time exposure of F/E angle > 30° was 164092 degree*second which can be converted to work for 91.2 minutes with deviated wrist posture of 30°.

Figure 6.42 and Table 6.33 show linear regression analysis between cumulative angle-time exposure of F/E angle > 30° and temperature-corrected peak latency change. The maximum allowable cumulative angle-time exposure of F/E angle > 30° on temperature-corrected peak latency was 38500 degree*second, which can be converted to work for 213.9 minutes with a deviated wrist posture of 30°.
Table 6.32 Regression analysis between peak latency and cumulative angle-time exposure of F/E > 30°

The regression equation is

$$\text{Peak Latency Change} = -0.0210027 + 0.0000022 \times \text{Cumulative Angle-time Exposure of F/E Angle > 30°}$$

$$S = 0.342711 \quad \text{R-Sq} = 11.9 \%$$

Analysis of Variance

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<tr>
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<td>Error</td>
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<td>6.34233</td>
<td>0.11745</td>
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<td>Total</td>
<td>55</td>
<td>7.19879</td>
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</tbody>
</table>
Figure 6.42  Association between temperature-corrected peak latency and cumulative angle-time exposure of F/E > 30°

Table 6.33  Regression analysis between temperature-corrected peak latency and cumulative angle-time exposure of F/E > 30°

<table>
<thead>
<tr>
<th>Source</th>
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<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
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<td>0.24410</td>
<td>0.24410</td>
<td>6.87</td>
<td>0.012</td>
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<td>Residual Error</td>
<td>50</td>
<td>1.77771</td>
<td>0.03555</td>
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<tr>
<td>Total</td>
<td>51</td>
<td>2.02181</td>
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</table>
6.9 Associations between Sensory Nerve Conduction and Subject Characteristics

Correlation analyses were performed using the Pearson’s technique between sensory nerve peak latency change and subject characteristics across workload conditions and participants at a significant level of \( \alpha = 0.05 \). Peak latency difference between time = 0 and time = 180 was used as a dependent variable to investigate the relationship between them. Results attained are shown in Table 6.34. Findings of the correlation analyses on peak latency and temperature-corrected peak latency were not significant for subject characteristics. Among them, the age had a positive relationship, though not significant \((r=0.217, p=0.123)\) with peak latency change, where sensory nerve peak latency change appears to increase as age increases. Also, the maximum pinch grip strength had a weak positive relationship, though not significant \((r=-0.230, p=0.078)\) with peak latency change, where sensory nerve peak latency change appears to decrease as maximum pinch grip strength increases.
Table 6.34  Correlation analysis between peak latency and subject characteristics

<table>
<thead>
<tr>
<th>Subject Characteristics</th>
<th>Nerve Conduction Variables</th>
<th>Nerve Conduction Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak Latency</td>
<td>Temperature-corrected Peak Latency</td>
</tr>
<tr>
<td></td>
<td>r</td>
<td>p</td>
</tr>
<tr>
<td>Age</td>
<td>0.217</td>
<td>0.123</td>
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<tr>
<td>Weight</td>
<td>0.076</td>
<td>0.564</td>
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<td>Statue</td>
<td>0.013</td>
<td>0.921</td>
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<tr>
<td>Body Mass Index (BMI)</td>
<td>0.075</td>
<td>0.568</td>
</tr>
<tr>
<td>Hand Length</td>
<td>0.166</td>
<td>0.206</td>
</tr>
<tr>
<td>Hand Breadth</td>
<td>-0.156</td>
<td>0.234</td>
</tr>
<tr>
<td>Hand Thickness</td>
<td>-0.055</td>
<td>0.676</td>
</tr>
<tr>
<td>Wrist Breadth</td>
<td>0.059</td>
<td>0.655</td>
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<tr>
<td>Wrist Depth</td>
<td>-0.053</td>
<td>0.688</td>
</tr>
<tr>
<td>Maximum Power Grip Strength</td>
<td>-0.062</td>
<td>0.635</td>
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<tr>
<td>Maximum Pinch Grip Strength</td>
<td>-0.230</td>
<td>0.078</td>
</tr>
</tbody>
</table>

6.10  Associations between Sensory Nerve Conduction and Room Temperature

Room temperature was carefully monitored and recorded as frequently as skin temperature measurements. The results of room temperature during task performance were calculated across participants for each condition, and are shown in Figure 6.43. The standard error bars are also presented for each workload condition. A very slight increase
in room temperature was observed over all workload conditions. The observed increases are presumed to be due to the both occupation of the room and use of heat-producing electronic equipment, such as EMG machine and computer.

Correlation analysis was performed using the Pearson’s technique between sensory nerve peak latency and room temperature across workload conditions and
participants at a significant level of \( \alpha = 0.05 \). The results presented in Table 6.35 indicated that the associations between room temperature and sensory nerve peak latency and temperature-corrected peak latency were not significant at \( p=0.05 \), even though sensory nerve peak latency appears to decrease as the room temperature increases.

Table 6.35  Correlation analysis between peak latency and room temperature

<table>
<thead>
<tr>
<th>Variable</th>
<th>Nerve Conduction Variables</th>
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<tr>
<td></td>
<td>Peak Latency</td>
</tr>
<tr>
<td></td>
<td>( r )</td>
</tr>
<tr>
<td>Room Temperature</td>
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Chapter 7

DISCUSSION

This chapter is organized in a topical manner by interpreting the findings of study where explanations of findings are discussed with considerations to limitations of the study.

7.1 Subject Sample

This study recruited fifteen subjects between the ages of 19 and 35 from a student population. Therefore they clearly were not representative of the general working population. As such, the findings presented herein, may not be generally applicable. Literature indicates a higher prevalence of carpal tunnel syndrome among female populations, where Nathan et al. (1992) reported that carpal tunnel syndrome is more common in females than males with a ratio of 2 to 1. Also the risk of carpal tunnel syndrome increases with aging, where Stevens et al. (1988), Tanaka et al. (1988), and Phalen (1972) found that active workers over 40 years old are 20 percent more at risk than younger workers. Since this study included only two female subjects and did not include any participant over 40 years old, the nerve conduction results might be more
sensitive if such subjects had been included. Therefore, future research should include broader samples of subject population.

7.2 Wrist Workload Measurement

Although visual and auditory feedbacks to perform required task condition were provided to participants for whole three hours task performance, workload measurements were recorded for only two periods of first and last ten minutes of task performance. This was due to the complexity of data acquisition, large data storage and the durability of electrogoniometer. Though the electrogoniometer is relatively small and lightweight offering quick and objective measurements of wrist joint motions (Nicole 1987; Ojima et al., 1991; Hansson et al., 1996; Buchholz and Wellman, 1997), its durability for three hours task is questionable. In future research activity, the workload measurement should acquire as frequently as nerve conduction measures.

7.2.1 Wrist Flexion/Extension Angle, Angular Velocity and Acceleration

The results of wrist workload measurement indicated that maximum angular flexion angles for low force conditions (0%MVC) were higher than those of high force condition (20%MVC). This finding is substantiated by the fact that the force factor accounted for 72% of the total sum of squares within subject variability. This may indicate a natural tendency to reduce tensile strain on the median nerve and tendons when
participants performed pinch force exertions for high force conditions, where Armstrong and Chaffin (1979a) and Siverstein et al. (1987) reported that tasks that require forceful exertion place higher loads on the muscle, tendons, median nerve, ligaments and joints. Moreover, internal loading induced during pinching tasks can result in up to 50 percent more force in first and second flexor tendons adjacent to median nerve compared to that of fingertip pressing tasks for identical external forces (Chao, 1976; Smith et al., 1977). It is also interesting to note that maximum angular extensions across participants were slightly greater than maximum angular flexion.

The total range of motion summed over each condition was ordered by low force-low repetition (0%MVC, 22RPM; LOF.LOR), low force-high repetition (0%MVC, 50RPM; LOF.HIR), high force-low repetition (20%MVC, 22RPM; HIF.LOR), and high force-high repetition (20%MVC, 50RPM; HIF.HIR) conditions that were somewhat greater that prescribed 120-degree arc of motion. This result indicated that the high repetition conditions as well as high force conditions produced a smaller maximum range of motion. The reason may be explained by the fact that the high repetition conditions and high force conditions make it difficult for subjects to perform the required wrist movements.

As expected, mean angular velocity, peak angular velocity, mean angular acceleration, and peak angular acceleration were greater for high repetition conditions compared to those for low repetition. One the other hand, the mean angular velocity and
angular acceleration for low force conditions were slightly higher than those for high force condition, since the pinch force exertion may interfere with wrist movement.

7.2.2 Cumulative Time and Cumulative Angle-time Exposure

Cumulative time was calculated to represent the accumulated time over the three hours of task performance when participant performed wrist movement beyond neutral position with different threshold angle criteria of 30°, 35°, 40°, and 45°. The cumulative time was highest in LOF.LOR, followed by LOF.HIR, HIF.LOR, and HIF.HIR for 30°, 35° and 40° thresholds. This result was very similar to the result of total range of motion, since the cumulative time was derived from the range of motion measurement and time interval. However, the cumulative time appears to be more adequate measure as a risk factor than the range of motion because the cumulative exposure time includes the time factor as well as wrist angular deviation factor during task performance.

Cumulative angle-time exposure was defined by the accumulated time × angle in this study when participants performed wrist movement beyond neutral position with different thresholds of 30°, 35°, 40°, and 45°. Thus, the cumulative angle-time exposure can be also used as a risk factor since the cumulative angle-time exposure showed to have a significant relationship with nerve conduction change.

However, the cumulative angle-time exposure might be a little complicated to use as a risk factor for ergonomic practitioners compared to cumulative time, because the
cumulative angle-time exposure is calculated as the product of the time interval and the deviated wrist angle when wrist is held over certain extreme posture. If a risk factor is too difficult to measure and compute, the practitioners may pursue other tools or measures for job evaluation and redesign at the workplace. On the other hand, the cumulative time can be considered relatively practical because it is just the time interval for which the wrist is deviated over a threshold angle. Therefore, it can be easily measured.

7.3 Median Sensory Nerve Conduction Change

7.3.1 Onset Latency and Peak Latency

Onset latency is the time between nerve stimulation and initial onset of waveform while peak latency is the time between nerve stimulation and peak point of waveform. Therefore, their highly significant correlation was expected, peak latencies over time (i.e. duration of exposure to workload) showed responses very similar to onset latencies. However, the onset latency might be mismeasured due to signal artifact and a false onset point while peak latency is able to accurately identify the point of highest amplitude along the waveform. Therefore, the reliability of onset latency as an objective measure of median nerve function is questionable.

The results indicated that mean initial peak latency at time = 0 across participants were similar across workload conditions, however exposure to wrist workload produced a noticeable difference. Peak latencies for low force-low repetition (LOF.LOR), high force-
high repetition (HIF.LOR), and low force-high repetition (LOF.HIR) conditions increased during the three hours of task performance, while little change was found for HIF.HIR condition. It was also interesting to note that the peak latency increased linearly during whole three hours of task performance, and significant (p<0.05) changes in peak latency for the LOF.LOR, HIF.LOR, and LOF.HIR conditions occurred after 60 minutes of exposure to wrist workload. The results of overall increases in latency over time (duration of exposure to workloads) in present investigation support the finding of Lloyd (1999) who reported that latency increased over duration of exposure to workload stressors.

However, the results also revealed that the latency change in low force conditions were significantly greater than those in high force conditions, and the latency change in low repetition conditions were significant larger than those in high repetition conditions. These were unexpected results, because the principle hypothesis of this study was that median nerve function decreases as wrist workloads increases. It is therefore suggested that the observed effects of force and repetition on latency changes may be, in part, due to the interaction of workload, heat gain and air flow to the hand with changes in skin temperature affecting nerve conduction measures. However, since the physiological thermoregulation on hand is controlled by nervous centers, the central thermoregulation is quite neurochemically complicated and is still far from being completely understood.

Manual work is likely lead to increasing blood flow to the hand, therefore to heat gain. The temperature gains during manual work may be counteracted by airflow over
hand, producing a convective and possibly evaporative effect. In a closed environment, the heat gain is directly proportional to the force exertion and repetitive movement. Therefore, it is postulated that in moderate hand repetition work, the effect of air flow on hand may exceed the temperature gain from the repetitive work. Reversely, in high repetitive work, temperature gain from work may surpass the effect of air flow on the hand. The explanation may be also supported by study of Christensen and Nielson (1942), who reported that the moderate activity in the sympathetic adrenergic vasoconstrictor fibers reduces the blood flow to skin where the blood flow and skin temperature in index finger decreased during work on a cycle ergometer.

Same explanations can be applied to the case of the force exertion, too. Temperature gain from a high force condition may exceed the airflow effect on the hand, while the airflow effect to the hand may surpass the temperature gain from a no force condition. Astrand and Rodahl (1986) indicated that the arterial blood pressure increases abruptly with sustained isometric effort at 15 percent of the maximum voluntary contraction (MVC) or higher. The blood pressures increase more or less linearly with the developed force in a given muscle group, and the arterial blood pressure at a given cardiac output is higher during isometric contraction than during dynamic exercise.

Thus, the temperature gain derived from rapid repetitive movements and highly forceful exertions have nerve conduction latency decreased, it may counteract the prolongation of peak latency which is thought to be induced from highly repetitive and forceful wrist movements. In fact, the temperature gain may mask the developing effects
of carpal tunnel syndrome caused from high force and high repetition conditions. The high force-high repetition (HIF.HIR) results may be understood by these explanations.

It was interesting to note that the order of peak latency changes among the four workload conditions during the three hours of task performance was accordance with that of the range of motions measurements which ordered by LOF.LOR, LOF.HIR, HIF.LOR, and HIF.HIR. These results mean that the peak latency change may be affected by the awkward wrist posture during prolonged periods of time. Thus, the high force-high repetition condition (HIF.HIR) results might be contrary to what would be expected, because full range of motions was not attained for the HIF.HIR condition.

Figure 7.1 describes these relationships in more details. The presentation of risk factors such as forceful exertion and repetitive wrist motion with range of motion during prolonged period of time without sufficient recovery time may cause pressure, fatigue and discomfort to carpal tunnel, and eventually may cause the prolongation of median sensory nerve latency. On the other hand, the heat gain from manual work as well as the airflow to the hand might change the hand temperature, and eventually may change the sensory nerve conduction latency. Also, as interactions between the risk factors and temperature changes, the temperature gain during forceful and repetitive movements may counter-effect the prolongation of peak latency, therefore, it may lead to mask the developing effects of carpal tunnel syndrome. Therefore, the effects of workload on nerve conduction measures can be both direct and indirect.
7.3.2 Amplitude

Like relationship between onset latency and peak, the onset amplitude (amplitude of onset to negative peak) and peak amplitude (amplitude of negative to positive peak) produced very similar results. However, amplitude measure might be influenced by several external as well as internal variables, including electrode placement, skin
conductivity, sweating, and stimulus level. The high standard errors for all workload conditions may support this explanation. Therefore, the reliabilities of both amplitude measures as the objective measure of median nerve function are also questionable.

By the way, the results indicated that amplitude increased for all workload conditions during first 60 minutes into task performance, but after that time, the amplitude stayed relatively level. This result of overall increase during first 60 minutes was also unexpected. Therefore, similar to peak latency, it may be also explained by the complicated relationships between workload, heat gain, air flow to the hand, skin temperature and nerve conduction measure.

On the other hand, the insignificant difference after 60 minutes may be, in part, explained by the relationship between focal cooling and diffuse cooling. In study of skin temperature effect on nerve conduction measures, Rutkove (2001) reported that cooling restricted to wrist and hand with index finger maintained at 34°C demonstrated prolongation in distal latency and minimal change in amplitude, while focal cooling restricted to index finger with hand and wrist maintained at 34°C demonstrated a predominant effect on amplitude and to a lesser extent, distal latency. Therefore, it is postulated that the skin temperatures of hand and index finger may decrease during first 60 minutes due to several reasons, but the skin temperature of index finger appears to be stayed level after that time while the hand temperature continues to decrease.
7.4 Median Motor Nerve Conduction

The results of the median motor nerve onset latency indicated that mean initial onset latency at time = 0 across participants were similar across workload conditions, however exposure to wrist workload produced a noticeable difference in onset latency. Like results of sensory nerve onset latency, onset latencies for LOF.LOR, HIF.LOR, and LOF.HIR conditions significantly increased, while little change was found for HIF.HIR condition. However, interestingly, unlike results of sensory nerve amplitude, no significant changes in amplitude were detected for all workload conditions. This results were in part supported by the study of Rutkove (2001) who indicated that temperature-related effects on motor nerve amplitude tend to be more modest than these observed in sensory nerve amplitude studies.

7.5 Temperature Effect on Nerve Conduction

As expected, skin temperature had a profound effect on nerve conduction measures. The general pattern of the skin temperature graphs was similar to the reverse graph of peak latency suggesting a possible correlation between the measures. Skin temperature had highly significant correlation relationship with peak latency (p<0.001, \( R^2=0.736 \)), where peak latency appears to increase as skin temperature decreases. This means that the results of prolonged peak latency obtained during the three hours of task performance might be influenced by skin temperature changes. Also highly significant
correlation between skin temperature and amplitude (p<0.001, R^2=0.284) was detected. These finding are in accordance with these in the studies of Rutkove (2001), Burke et al. (1999a), Asworth et al. (1998), Rutkove et al. (1997), Letz and Gerr (1994), Baysal et al. (1993), Lee et al. (1993) and Tashjian et al. (1987). In their studies, they reported that as the skin temperature decreases, the nerve conduction action potential recorded from a nerve demonstrates an increased amplitude and prolonged latency. These observations are highly suggestive of a possible association between thermoregulation of the hand and sensory median nerve performance as explained in section 7.3. Evidence in the literature pertaining to ischemic involvement in the etiology of carpal tunnel syndrome supports these observations.

On the other hand, the physiological mechanism between temperature change and nerve conduction measures was reported by several researchers (Rutkove, 2001; Burke et al., 1999a; Burke et al., 1999b, Rutkove et al., 1997). The effect of temperature on sensory and motor nerve action potentials as first reported by Hodgkin and Katz in 1949, is largely due to alternations in Na^+ (sodium) channel function on neuronal resting membrane where K^+ (Potassium) is sequestered within the cell while Na^+ is pumped out. They reported that temperature appears to have only a modest effect on neuronal resting membrane potential. But the abrupt inward flux of Na^+ ions produce the depolarization of a single nerve axon. This influx of Na^+ ions may occur due to the opening of voltage-gated channels along the axon or to the binding of a neurotransmitter as occurs on the muscle endplate. Following the initial influx of Na^+ ions, the Na^+ channel closes and K^+
channel opens, allowing for a small efflux of potassium, restoring the membrane to its
resting potential. Repeated depolarizations of a cell will eventually decrease the potential
gradient. In order to counteract this decrease, the Na\(^+\)/K\(^+\) adenosine triphosphatase
(ATPase) is constantly pumping out Na\(^+\) and bringing in K\(^+\), helping to maintain the
resting potential. Thus, a decrease in temperature slows down both the opening and
closing of the Na\(^+\) channel, with the closing being more affected than the opening. This
phenomenon has several effects. First, the slower depolarization translates into a
prolonged latency for the axon. Second, the slower depolarization and repolarization
produces a longer channel-open time and, therefore, a longer duration response. Finally,
as additional ions move into the cell during the prolonged opening, a larger
depolarization occurs and the response amplitude increases.

7.6 Temperature Corrected Median Sensory Nerve Conduction

Reference values for skin temperature correction vary by methods performed. Available correction factors for median sensory nerve conduction using antidromic nerve
conduction technique are listed in Table 7.1. Among these studies, Lee et al. (1993) used
the same measurement techniques and very similar sites for skin temperature
measurements. To test the effect of skin temperature on median sensory nerve peak
latency and amplitude, the skin temperature was measured on the palmar surface of the
proximal part of the index finger instead of the palmar surface of the metacarpal bones of
the index finger in this study. Therefore, Lee’s et al. (1993) correction factor was used to adjust the temperature effect on sensory nerve peak latency. On the other hand, for sensory nerve peak amplitude correction, Tashjian’s et al. (1987) study was used. However, as indicated in previous sections, nerve conduction measures may be influenced by many external factors as well as internal factors, including electrode placement, skin conductivity, sweating, stimulus level, equipments used, measurement techniques, electrode impedance, stimulus intensity and duration, etc. Therefore the correction factors may not be applicable to this study.

Table 7.1 Correction factors for antidromic median sensory nerve conduction with skin temperature change

<table>
<thead>
<tr>
<th>Authors</th>
<th>Stimulation site</th>
<th>Recording site</th>
<th>Distance between stimulation and recording</th>
<th>Latency measurement</th>
<th>Amplitude measurement</th>
<th>Site for skin temperature measurement</th>
<th>Correction factor</th>
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<tbody>
<tr>
<td></td>
<td>Cathode</td>
<td>anode</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lee et al. (1993)</td>
<td>Wrist</td>
<td>2nd digit</td>
<td>4cm</td>
<td>14cm</td>
<td>Peak latency</td>
<td>Proximal phalanx of index finger</td>
<td>0.1msec 1.75µV</td>
</tr>
<tr>
<td>Tashjian et al.</td>
<td>Wrist</td>
<td>2nd digit</td>
<td>4cm</td>
<td>14cm</td>
<td>Peak latency</td>
<td>Amplitude of negative to positive peak</td>
<td>0.06msec 3.5µV</td>
</tr>
<tr>
<td>Halar et al. (1983)</td>
<td>Wrist</td>
<td>2nd digit</td>
<td>4cm</td>
<td>14cm</td>
<td>Peak latency</td>
<td>Not given</td>
<td>0.2msec Not given</td>
</tr>
<tr>
<td>Bolton et al. (1982)</td>
<td>Wrist</td>
<td>2nd digit</td>
<td>Non-specified</td>
<td>Onset latency</td>
<td>Amplitude of onset to negative peak</td>
<td>Proximal phalanx of index finger</td>
<td>0.07msec 1.9µV</td>
</tr>
</tbody>
</table>
By the way, the results of median sensory nerve peak latency after skin temperature correction indicated that skin temperature-corrected peak latency over time (i.e. duration of exposure) produced results very similar to the measured peak latency, even though the slope for each workload condition was adjusted. However, the results still indicated that latency change in low force-low repetition condition was greater than those in high force-high repetition condition. Therefore, these results would be explained by the relationships between sensory nerve peak latency and workload variables such as the total range of motions and cumulative time.

On the other hand, the result of prolongation of temperature-corrected peak latency may mean the temporal focal demyelination of median nerve due to the recurrent compression to carpal tunnel, since the temperature corrected peak latency still showed prolonged distal latency response. Isley et al. (1993) indicated that for individual myelinated nerve fibers, focal demyelination cause conduction slowing. With conduction slowing, nerve impulses traverse at a slower rate than normal because, due to myelin damage, a greater amount of the axon at the node has to be depolarized; this consumes time.

The results of median sensory nerve peak amplitude after skin temperature correction corresponding to Tashjian et al. (1987) revealed that for all workload conditions skin temperature-corrected amplitude showed an overall increase until 60 minutes, but after that the skin temperature-corrected amplitude showed decreased trends.
Due to the high variance, however the amplitude changes over time were not significant except for HIF.LOR and HIF.HIR conditions.

Therefore, this result may suggest that the exposure to workload stressors during a three-hour task performance might not cause axon-loss lesions to median nerve. Isley et al. (1993) indicated that the amplitude of the nerve conduction response is a semiquantitative measure of the number of nerve fibers capable of conducting impulses between the stimulating and recording sites. They are, therefore, affected by axon-loss lesions located at any point. Consequently, diminution of sensory nerve action potential amplitudes is the most sensitive indicator of axon-loss lesions. Also Rasminsky (1973) reported that decrease in amplitude of a compound action potential may represent blockage of conduction of some of the fibers contributing to the compound action potential and/or increased temporal dispersion due to unequal slowing of conduction in the various fibers contributing to the compound action potential. However, this is differed from results of this study, since little change in amplitude was found for all workload conditions.

In conclusion, since axon-loss lesions affect primarily the amplitude of the sensory nerve response, while focal demyelination affects the latency, and the results showed the prolonged latency and little change of amplitude, this study may indicate the possibility of temporal demyelinating focal slowing on median nerve within carpal tunnel during the three hours of task performance. Also, the characteristic electrophysiological feature of carpal tunnel syndrome is focal slowing of impulse conduction across the
carpal tunnel, and if results of this study may mean the temporal demyelinating focal slowing, this study may propose a concept of a dynamic carpal tunnel syndrome.

7.7 Regression Analysis between Sensory Nerve Conduction and Time

The limits of normal for conventional nerve conduction studies used in the diagnosis of CTS are inconsistent depending on studies, because each laboratory obtains its own normal values using different nerve conduction procedure, equipments, and subjects. Among previous studies, Jackson and Clifford (1989) used the same nerve conduction techniques as this study and the results of mean peak latency were very similar (3.16 msec vs 3.10 msec). They utilized a reference value of 3.5 msec for peak latency as the limit of normal range.

Assuming the limit of normal peak latency, the peak latencies measured under the LOF.LOR and LOF.HIR conditions approached the reference value diagnostic for clinical evidence of carpal tunnel syndrome before the completion of the three-hour task (67 and 163 minutes, respectively). On the other hand, even though the temperature-corrected peak latency did not attained the empirical lower limit of normal range within three hours of task performance, the results of increased peak latencies for LOF.LOR, HIF.LOR, and LOF.HIR conditions can cause some cumulative effects on the wrist if such conditions continue repeatedly for a long period of time. It is proposed therefore, that sufficient recovery time be provided to restore normal nerve conduction measures.
7.8 Peak Latency Shift

It was very interesting to note that 67 percent of participants had temporary peak latency increases beyond 3.5 msec when they worked in the low force and low repetition condition. When it was assumed that the skin temperature remained fairly level during the three-hour task, the probability fell to 32 percent, which is, however, still a very high value. It was assumed that the peak latency measurements follow normal distribution because the peak latency measures passed the Kolmogorov-Smirnov normality test with a small sample size. However, the peak latency might not follow the normal distributions, therefore, the finding presented herein may not be applicable.

7.9 Associations between Sensory Nerve Conduction and Workload Variables

Correlation analyses between workload variables and peak latency indicated that maximum wrist flexion angle, maximum wrist range of motion, cumulative time and cumulative angle-time exposure had highly significant relationships with peak latency over time. Among these relationships, the most interesting and significant correlation was presented between cumulative time variable of F/E angle > 30° and sensory nerve peak latency \( r=0.3715, \ p=0.005 \) where sensory nerve peak latency increased as the cumulative time of F/E angle > 30° increased. This relationship is perhaps the most important by-product of this study, since the peak latency change can be explained by the
cumulative time factor as well as wrist angular deviation factor. Regression analysis indicated that if the workload condition of the task made wrist to be held in extreme posture over 30° for 125 minutes, it may impede sensory median nerve function diagnostic clinical evidence of carpal tunnel syndrome. Thus, the cumulative time of F/E angle > 30° may serve as a useful measure for investigating the effect of occupational exposures on median nerve.

On the other hand, since the cumulative angle-time exposure for F/E angle > 30° showed a highly significant relationship with nerve conduction velocity changes, it also can be used as a useful measure for evaluating CTS. However, as mentioned previously, cumulative angle-time exposure might be a little difficult for ergonomic practitioners to use for job evaluation compared to cumulative time. Due to its ease of use, therefore, we suggest cumulative time of F/E angle > 30° as the best measure for investigating the effects of dynamic wrist workloads on the nerve conduction, hence the prevalence of CTS.

7.10 Associations between Sensory Nerve Conduction and Subject Characteristics

Correlation analyses on peak latency and all subjective characteristics did not find any significant variables for α=0.05. Contrary to present study, however, Kuhlman and Hennessey (1997), Stetson et al. (1992) and Trojaborg et al. (1992) reported that nerve
conduction had significant correlation relationships with stature and BMI (Body mass index). This may be due to difference of sample size and sampling population.

On the other hand, the age had a positive relationship, though not significant ($r=0.217$, $p=0.123$) with peak latency change, where sensory nerve peak latency increased as the age increased. The slowing of median peak latency with increasing age was previously reported by several studies of Letz and Gerr (1944), Nathan et al. (1992) and Stetson (1992). Nathan et al. reported that the latency was found to increase by 0.04 msec per decade in age. Therefore, it is further suggested that the correction factor for age should be used in calculation of median nerve conduction to increase the sensitivity and specificity of evaluations, if the correlation is highly significant.

7.11 Associations between Sensory Nerve Conduction and Room Temperature

The results indicated that the associations between room temperature and sensory nerve peak latency were not significant at $\alpha=0.05$, even though sensory nerve peak latency appears to decrease as the room temperature increases. However, because other studies have reported that ischemia (localized tissue anemia due to obstruction of the inflow of arterial blood) involved the etiology of carpal tunnel syndrome, a true positive association may exist between nerve conduction and environmental temperatures. Therefore, further research investigates the effects of environmental temperature on nerve conduction.
Chapter 8

CONCLUSIONS

8.1 Summary of Results

The effects of dynamic wrist workloads on nerve conduction measures were examined with fifteen participants over 3 hours duration of exposure, where the subject performed repetitive flexion/extension movement accompanied by intermittent pinch force exertion. The nerve conduction results indicated that mean initial peak latency at time = 0 across participants were similar across workload conditions, however exposure to wrist workload over three hours task performance produced a noticeable difference. Overall increases in peak latency for low force-low repetition (LOF.LOR), high force-high repetition (HIF.LOR), and low force-high repetition (LOF.HIR) conditions during three hours task performance were detected, while little change was found for high force-high repetition (HIF.HIR). It was also interesting to note that significant measurable changes in peak latency for the LOF.LOR, HIF.LOR, and LOF.HIR conditions first occurred after 60 minutes of exposure to wrist workload.

Even though the results also indicated that the peak latency changes in low force conditions were greater than these in high force conditions, and the latency changes in low repetition conditions were larger than those in high repetition conditions, the
observed effects of force and repetition on latency changes could be explained by the relationships of workload, heat gain and air flow to the hand with changes in skin temperature affecting nerve conduction measures. Thus, specifically, the temperature gain derived from rapid repetitive movements and highly forceful exertions may counteract the prolongation of peak latency, and mask the developing effects of carpal tunnel syndrome which is thought to be caused from highly repetitive and forceful wrist movements.

It was also interesting to note that the order of peak latency changes among the four workload conditions correlated with the range of motion measurements in ordered of LOF.LOR, LOF.HIR, HIF.LOR, and HIF.HIR. These results mean that the peak latency change may be more affected by the range of motion during prolonged periods of time rather than the force and repetition. Thus, the high force-high repetition condition (HIF.HIR) results might be contrary to what would be expected, because full range of motions was not attained. Highly significant correlation results between sensory nerve peak latency and the total range of motions, and cumulative time of F/E angle > 30° support this explanation.

As expected, skin temperature had a profound effect on nerve conduction measures. The results of median sensory nerve conduction after skin temperature correction indicated that the temperature-corrected peak latency over time produced similar results to the measured peak latency. Little changes in skin temperature-corrected amplitude were found for all workload conditions. Therefore, this result may indicate that
the exposure to workload stress during three hours of task performance may not cause the axon-loss lesions to median nerve, but instead it may cause temporal demyelinating focal slowing of median nerve within carpal tunnel during the three hours of task performance.

Assuming the limit of normal peak latency (3.5 msec), the peak latency measured under the low force-low repetition (LOF.LOR) condition approached the reference value diagnostic of clinical evidence of carpal tunnel syndrome with 67 minutes of task performance, and 67 percent of participants had temporary peak latency increases beyond 3.5 msec when they worked in the low force and low repetition condition.

Correlation analyses between workload variables and peak latency indicated that maximum wrist flexion angle, maximum wrist range of motion, cumulative time and cumulative angle-time exposure had highly significant relationships with peak latency over time. Among these relationships, the most interesting and significant correlation was present between cumulative time variable of F/E angle > 30° and sensory nerve peak latency, where sensory nerve peak latency increased as the cumulative time of F/E angle > 30° increased. This relationship may be the most important output of this study, since the peak latency change can be explained by the cumulative time factor as well as the wrist angular deviation factor. Also, cumulative time can be considered practical because it can be easily measured with the time interval when wrist is deviated over a threshold angle. Regression analysis indicated that if the wrist deviation repetitively exceeded 30° for over 125 minutes, sensory median nerve impairment may approach diagnostic clinical evidence of carpal tunnel syndrome. Thus, the cumulative time of F/E angle > 30° may
serve as the best measure for investigating the effects of dynamic wrist workloads on the nerve conduction, hence prevalence of CTS.

8.2 Research Contributions

Several researchers reported that occupational risk factors including awkward posture, repetition motions, and forceful exertions cause a possible etiology for carpal tunnel syndrome. However, there are few research studies investigating the relationship between the occupational risk factors and the median nerve function.

First of all, this study demonstrated that exposure to wrist workload over three hours task performance produced a noticeable difference in median sensory nerve peak latency, and significant measurable change first occurred after 60 minutes of exposure to wrist workload.

Second, this research developed the quantitative dose-response relationship between occupational risk factors such as the cumulative exposure time of F/E angle over 30° and maximum range of motions, and median sensory nerve peak latency, therefore, CTS prevalence.

Third, this study provided the threshold limit to prevent carpal tunnel syndrome for occupational risk factors of the maximum range of motions and cumulative time of F/E angle over 30°.
Finally, this study suggested the cumulative time of F/E angle $> 30^\circ$ as the best useful measure for investigating the effects of dynamic wrist workloads on the nerve conduction, hence the prevalence of CTS.

8.3 Recommendations for Further Study

As with any substantive research, there appear to be as many new questions asked as answered. Several opportunities have been identified to further investigate issues relating directly to this research as well as to investigate unexpected new findings.

The first opportunity pertains to the application of research tools developed during this study for field studies such as meat-packers, automobile manufacturers and other industries with manual tasks. Unlike previous studies, however, this field study should involve more intensive measurements with nerve conduction measures would be recorded immediately before work starts and every 20 minutes during task performance to explore frequently changing median nerve measures.

Second, the research presented herein should be expanded by recruiting a large number of subjects including female subjects and broad range of age groups. As indicated previously, the nerve conduction measures might be more sensitive if the more females and older age groups were recruited. Even with both control and CTS patients, the research may evaluate the different response on median sensory nerve measure for workload stressors.
Third, a further study with a fewer division of force and repetition levels is also suggested. Present research was limited to only two levels for each variable to investigate the effect of workload variable primarily due to the long experimental time. Larger levels should be considered to produce a better results and refined analysis. Also, the cumulative time and range of motion variables should be added to future study for investigating the effects of dynamic wrist workloads on the nerve conduction. Thus, the future study might be performed in constant hand temperature, if possible.

Finally, since the skin temperature have significant relationship with nerve conduction measure, and the skin temperature is relied on the room temperature, the investigation of room temperature effects on nerve conduction measure could verify the dose-response relationship between cold temperature and prevalence of CTS.
REFERENCES


reported carpal tunnel syndrome in a national survey of the working population. 


APPENDIX A: INFORMED CONSENT FORM

INFORMED CONSENT FORM
The Pennsylvania State University

Protocol No: 01M0719-00
Date: September 17, 2001

Title of Project: The Effects of Dynamic Wrist Workloads on the Risks of Carpal Tunnel Syndrome (CTS)
Principal Investigator: Hyunkook Jang, Department of Industrial and Manufacturing Engineering, 310 Leonhard Building, University Park, PA 16802, (Phone 814-865-8073)
Other Investigators: Andris Freivalds, Ph.D., (Department of Industrial and Manufacturing Engineering)
Milind J. Kothari, D.O., (Division of Neurology, College of Medicine)

Thank you for your participation in this study. This research is being conducted as part of the doctoral dissertation research of Hyunkook Jang under the supervision of Dr. Freivalds, and Dr. Kothari.

This is to certify that I, ________________________________, have been given the following information with respect to my participation as a volunteer in a program of investigation under the supervision of Dr. Freivalds.

1. Purpose of the study: The purpose of this study is to investigate the relationship between dynamic wrist workloads (repetitious motions, and forceful exertions) and risks of carpal tunnel syndrome (CTS).

2. Procedures to be followed: You will be assisted by investigator to sit in a proper posture, upper arm vertical, forearm horizontal, i.e. 90 degree elbow angle (forearm at right angle for upper arm). An electrogoniometer (device capable of measuring wrist angular movement) will be attached with Velcro above and below your wrist. Also disposable electrodes will be attached to your right hand. Then you will be asked to bend your wrist back and forth maximally following an auditory beat (22 or 50 repetition per minute). During the repetitive wrist movements, you also will be asked to exert at times a target force (20% maximum effort or no effort) using the right thumb and
index finger to pinch a simulated tool. Feedback of the pinch force and wrist movement will be provided on the computer screen. Nerve conduction measures will be recorded using a standard measurement technique with the wrist and fingers in a straight posture. For sensory nerve conduction recording, an active ring electrode (black) will be placed on index finger, and a reference electrode (red) will be placed 4 cm distal to the active electrode. For the motor nerve response, an active disc electrode will be placed on the belly of the thumb muscle, and a reference electrode will be placed on the tendon of thumb muscle. For both sensory and motor nerve recordings, a large ground electrode will be placed on the palm between the stimulating and recording electrodes. The nerve conduction measures will be recorded immediately before the task starts and every 20 minutes therefore during task performance. You might feel a tingling sensation during nerve conduction test. The four workload conditions (two levels of repetitive wrist movements \( \times \) two levels of force exertions) will be presented randomly on one per day. Between sessions, you will be allowed a day of rest so as to recover the onset of fatigue. You will be also asked to rate your perceived comfort level, using the Borg scale during task performance.

3. Discomforts and risks: Discomfort or fatigue with the hand may occur from repetitive wrist motions. Nerve conduction test is a non-invasive test. However, you might feel a slight buzzing sensation in the wrist and fingertip of index finger. If you feel any significant discomfort, fatigue, and/or buzzing sensations on hand during participation, stop and inform the investigator.

4. Benefits to me: There are no benefits to me from my participation.
   b. Potential benefits to society: This study may contribute to establishing the threshold limits for dynamic workloads to prevent the development of carpal tunnel syndrome in industries.

5. Alternative procedures which could be utilized: No other alternative procedures will not be utilized.

6. Time duration of the procedures and study: Participation in this study will take approximately 12 hours.

7. Statement of confidentiality: My participation in this research is confidential. Only the investigators will have access to my identity and to information that can be associated with my identity. All records associated with my participation in the study will be subject to the usual confidentiality standards applicable to medical records, and in the event of any publication resulting from the research no personally identifiable information will be disclosed.
8. **Right to ask questions:** I have been given an opportunity to ask any questions I may have, and all such questions or inquiries have been answered to my satisfaction. Questions regarding the nature of the research should be directed to Dr. Freivalds (Phone: 814-863-2361).

9. **Compensation:** I will be compensated $5 per hour of the time for my participation in the study.

10. **Injury clause:** I understand that medical care is available in the event of physical injury resulting from research but that neither financial compensation nor free medical treatment is provided.

11. **Voluntary participation:** I understand that my participation in this study is voluntary. I am 18 years of age or old. I may withdraw from this study at any time by notifying the investigator. My withdrawal from this study or my refusal to participate will in no way affect my care or access to medical services.

This is to certify that I consent to and give permission for my participation as a volunteer in this program of investigation. I understand that I will receive a signed copy of this consent form. I have read this form, and understand the content of this consent form.

______________________________  ________________________
Volunteer Date

I, the undersigned, have defined and explained the studies involved to the above volunteer.

______________________________  ________________________
Investigator Date
APPENDIX B: SCREEN QUESTIONNAIRE

SCREENING QUESTIONNAIRE

1) Have you had any incidents of hand or wrist pain?
   YES  NO
   If yes, please explain

2) If your answer to question 1) was “yes”, have these incidents limited your physical activities?
   YES  NO
   If yes, please explain

3) Have you had any hand surgery?
   YES  NO
   If yes, please explain

4) If your answer to question 3) was “yes”, has this surgery limited your physical activities?
   YES  NO
   If yes, please explain

5) Are you suffering from any chronic disease (e.g. diabetes, epilepsy, etc.)?
   YES  NO
   If yes, please explain

______________________________  __________________________
Volunteer                      Date
VITA

Hyunkook Jang was born on January 10, 1966 in Pyongtaek, Kyongki, the Republic of Korea. He received a B.S. in Industrial Engineering from Inha University, Inchon, Korea in 1988, and an M.S. in Industrial Engineering from Seoul National University, Seoul, Korea in 1990. At Pennsylvania State University, he served as a graduate research assistant at the Center for Cumulative Trauma Disorders. His research interests are in human factors engineering, specifically in occupational job safety and health, ergonomic product design, biomechanics, and manufacturing system analysis. He is a member of the Human Factors and Ergonomics Society.