EFFECT OF WRIST ACTIVITY
ON MEDIAN NERVE FUNCTION

By

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ABSTRACT

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Keywords – work-related musculoskeletal disorders; carpal tunnel syndrome; median nerve; electroneurometry; repetitive hand and wrist activity; ergonomics; biomechanics.

Background -- Hand intense occupational activities have been associated with an increase in the incidence of carpal tunnel syndrome (CTS). CTS is characterized by an impairment of median nerve function. To date, a dose-response relationship between wrist activity and median nerve performance has not been documented. Since repetitive hand/wrist activity in the workplace has significant implications, it is important to establish a scientific basis for the aetiology of work-related carpal tunnel syndrome.

Methods -- In a laboratory environment, twenty-seven clinically confirmed asymptomatic female subjects performed continuous repetitive wrist motion in the flexion-extension plane during which an angle of 120 degrees was subtended about the neutral wrist position. Four levels of wrist activity, corresponding with 0 (static), 22 (low), 38 (medium) and 49 (high) repetitions per minute, were prescribed.

Wrist motion was recorded using a state-of-the-art 3D electromagnetic tracking system (HumanTRAC). Mathematical descriptors of wrist kinematics, including cycle time, amplitude, angular velocity and angular acceleration, were calculated. Sensory median nerve response to imposed physical stressors was monitored antidromically and recorded using a clinical electroneurometer every ten minutes throughout the simulated work activities. Near-nerve skin temperature was recorded at three sites along the distal sensory branch of the median nerve every twenty minutes.

Results – After adjusting for changes in near-nerve skin temperature, a significant within-subject effect of duration of exposure (time) was detected.

Sensory median nerve conduction velocity differed statistically by 2.1 ms^{-1} between the static and high wrist activity conditions after 120 minutes of exposure, signifying adverse effects on nerve conduction that are uniquely attributable to repetitive hand motion.

Wrist activity measures of mean angular acceleration presented a highly significant association with nerve performance, where nerve conduction decreased as wrist activity increased. Using regression analysis, a maximum safe wrist-workload exposure limit of 0.91 repetitions per minute is proposed. Limitations of this result are discussed.

A biomechanical model is presented to calculate the effect of physical risk factors on tendon forces at the wrist. This model offers a method by which findings of the study can be employed for workplace exposure surveillance and development of ergonomic workstation design recommendations.

Conclusions -- Across the study population of clinically asymptomatic female participants, a change in median nerve performance was observed. This significant effect was evoked due to imposed physical stressors. A dose response relationship between work intensity, exposure time and median nerve conduction velocity was demonstrated.

The research explored in this thesis presents a foundation for the future development of a "Dynamic Median Nerve Stress Test". This test would involve the performance of a repetitive motion activity of the wrist during which changes in the function of the median nerve are closely monitored. The Dynamic Median Nerve Stress Test might prove to be valuable both as a provocative clinical test as well as an important research tool.

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CHAPTER 1: INTRODUCTION

1.1 Overview

Restriction of the median nerve as it passes through the carpal tunnel, an anatomic passage in the wrist bridged anteriorly by the inelastic transverse carpal ligament, is the most common example of a nerve compression disorder. First described by Sir James Paget in 1854, this disorder is frequently termed carpal tunnel syndrome (CTS). Other terms used to describe the syndrome include writer's cramp, ape hand, occupational neuritis, partial thenar atrophy and median neuritis.

CTS is a multi-factorial process, where both occupational and personal factors may contribute to its development, leading to median nerve sensory and / or motor impairment. Symptoms may include tingling, numbness and/or pain in the median distribution of the hand.

The potential relationship between work tasks and the development of carpal tunnel syndrome has polarized many groups. Some experienced scientific investigators strongly oppose a causal relationship between hand intensive operations and median nerve pathology, citing the absence of supporting scientific data. Patient advocates reference cohort and cross-sectional studies in an effort to explain the development of carpal tunnel syndrome based on presented physical stressors.

Whether or not carpal tunnel syndrome is caused by hand and wrist activity during work has serious implications to patients, physicians, employers, insurance carriers and state and federal governments.

1.2 Statement of the Problem

During the past fifteen years, research activities investigating carpal tunnel syndrome have expanded as a result of increased incidence in the workplace. Much research into causative factors associated with work-related carpal tunnel syndrome has focused on epidemiological data. These studies have been valuable in providing identifying physical risk factors such as force,

repetition, vibration and posture that are believed to contribute to the disorder. However, the application of these data in the quantification of exposure limits is constrained by the questionable validity of the health outcomes data sources.

1.3 Current Status of Work in this Area

1.3.1 Quantification of Exposures

Several biomechanical studies have been performed to examine key pathomechanical factors associated with CTS development. Marras and Schoenmarklin (1991a) conducted an investigation into the relationship between dynamic wrist activities and incidence of upper extremity cumulative trauma disorders in an industrial setting. Wrist motions were recorded using an electrogoniometer, which monitored activities in the flexion-extension, ulnar-radial and pronation-supination planes. Mean velocity and acceleration during task performance was determined for each participant for each of the three planes of motion. Tasks were classified based upon low and high levels of wrist activity. Incidence of self-reported WR-CTS among participants was then mapped against recorded wrist motions. Their findings suggest that the magnitude of mean angular acceleration in the flexion/extension plane is a potential predictor of risk level. Using logistic regression, the investigators found that self-reported risk of developing CTS increased by 600 percent when wrist flexion-extension mean acceleration exceeded 824 deg s^{-2}, compared with exposures less than 490 deg s^{-2}.

Further analysis of the data using multiple regression analysis was used to construct a dose-response model to predict incidence of disorders as a function of wrist kinematics (Schoenmarklin and Marras, 1994). Threshold limits were proposed, where industrial operations involving peak angular wrist accelerations greater than 6,541 deg s^{-2} presented a 98% probability of self-reported CTS incidence among the sample.

1.3.2 Health Outcomes Measurement

Currently, the most reliable technique for assessing the severity of median nerve neuropathy in carpal tunnel syndrome is the electroneurological evaluation. Electroneurometers quantify nerve function by measuring the time required for a synthetic impulse to travel from a stimulus 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. Electrodiagnostic testing has become widely instituted and is used as the standard for the early detection of peripheral nerve disorders.

1.4 Voids in the Research Knowledge

Although numerous studies have suggested that work-related carpal tunnel syndrome develops due to prolonged exposure to force, frequency, posture and vibration stressors, no clear "dose-response" relationship has yet been determined between the amount or intensity of work and the incidence or severity of the syndrome (Katz, 1994; Hadler, 1997). Establishment of the work-relatedness of these disorders requires both the quantification of physical exposures and a reliable objective determination of health outcomes.

The evidence in the literature presents agreement between epidemiological and biomechanical findings for occupational risk factors of forceful exertion and awkward posture. Task repetition may be the single greatest risk factor associated with the prevalence of carpal tunnel syndrome among working populations, however, biomechanical studies to date have failed to address this important issue independent of other factors. This research study considers the effect of repetitive wrist motion on median nerve function exclusive of other contributory physical factors.

1.5 Basis for Research

Theoretically, with advanced objective surveillance tools, high-risk operations could be systematically identified and the incidence of CTS reduced through appropriate ergonomic interventions.

Objective techniques need to be developed to clearly define the dose-response relationships between levels of exposure to suspected contributory stressors and the development of work-related carpal tunnel syndrome. Through the systematic evaluation of occupational risk factors, safe and unsafe levels of wrist-workload could be documented as a function of presented stressors and duration of exposure. This would facilitate the establishment of threshold limit values for mechanical agents of the carpal tunnel.

Recent enhancements in computer-based data acquisition systems have made accurate monitoring of kinematic wrist motions possible with high fidelity. Simultaneous improvements in computer hardware and software enable reduction and analysis of the inordinate quantities of data that are recorded. Advancements in electrophysiological measurement systems have significantly enhanced patient tolerance for its use and improved the sensitivity and repeatability of nerve conduction measures to objectively measure functional status. Given the technological capacity to precisely measure both exposures (dose) and health outcomes (response) it is now possible to quantify and better understand the underlying dose-response relationships in carpal tunnel syndrome.

1.6 Goal

The goal of this study was to determine if a threshold shift in sensory nerve function could be systematically produced with exposure to physical stressors. If achieved, this could facilitate the development of mathematical models to establish safe wrist-workload exposure limits as a function of presented stressor(s) and duration of exposure for hand intensive operations.

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1.7 Hypothesis

This research study investigated the hypothesis that <u>median nerve function decreases as wrist activity increases</u>.

CHAPTER 2: OVERVIEW OF CARPAL TUNNEL SYNDROME

The following review of the literature is broken down into two sections. Chapter 2 presents an overview of carpal tunnel syndrome, with regard to its anatomy and physiology, medical evaluation, with specific emphasis on electrodiagnostic techniques, treatment opportunities, incidence and costs. Chapter 3, documents current etiological understanding of the syndrome, upon which voids in the research knowledge are identified.

2.1 Work-Related Musculoskeletal Disorders

Work-related musculoskeletal disorders (WMSDs) are physiological illnesses that may develop over a period of weeks, months, or even years due to prolonged mechanical stresses imposed on the musculoskeletal system. These disorders may also be referred to as "repetitive strain injuries (RSI)" (Kiesler and Finholt, 1988), "over use injuries" (Green and Briggs, 1989), or "repetitive motion injuries" (US Department of Labor, 1990).

WMSDs are considered work-related since they are more prevalent among the working population than the general public. Often, due to slow onset, the microtrauma is ignored until the symptoms become chronic and permanent injury occurs (Putz-Anderson, 1988).

The "worker's disease" was first documented in 1717 by Ramazinni, a physiologist, who described the problem thus:

> "Various and manifold is the harvest of diseases reaped by certain workers from the crafts and trades they pursue. All the profit that they get is fatal injury to their health ... [which] ... I ascribe to certain violent and irregular motions and unnatural postures of the body, by reasons of which, the natural structure of the vital machine is so impaired that serious diseases gradually develop therefrom."

The development of such occupational illnesses in high-risk industries has been recognized and monitored for some time. Although slight, when compared with acute manual handling injuries, the problem escalated exponentially during the 1980's (Green and Briggs, 1989) and fears that work-related musculoskeletal disorders may play a significant part in future worker's compensation claims (Brogmus and Marko, 1990; Brogmus et al, 1994) are being realized. Several theories to substantiate this upward trend have been suggested, not least of which is a rise in symptomatic reporting due to increased public awareness (Snook, 1990; Bernstein, 1994; Brogmus, 1995; Brogmus et al, 1996).

2.1.1 Description and Classification of Musculoskeletal Disorders

Three basic types of cumulative disorders to the musculoskeletal system are classified according to the anatomical source of irritation: tendon, nerve, and neurovascular.

2.1.1.1 Tendon Disorders

Tendon disorders are those ailments associated with overuse or unaccustomed use of a specific body part.

2.1.1.2 Nerve Disorders

Nerve disorders are attributable to repeated or sustained work activities that, over time, cause partial or complete loss of sensory or motor nerve function, due to pressure against the nerve from adjacent musculoskeletal structures. Carpal tunnel syndrome is the most common example of a nerve compression disorder.

2.1.1.3 Neurovascular Disorders

Neurovascular disorders involve the compression of both nerves and neighboring blood vessels, which can produce symptoms similar to those of nerve disorders.

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2.2 Anatomy and Physiology

2.2.1 Structures of the Hand and Wrist

The working arm derives motion and leverage from the skeleton and muscles at three major joints: wrist, elbow and shoulder. This structure is amazingly versatile, capable of a wide range of movement. It is exceptionally strong for its size and yet is capable of the most delicate and precise manipulative skills using a variety of handgrips. The arm is so strong that it can conceivably damage itself.

The upper limb skeletal system consists of thirty-two bones, twenty-seven of which are found in the hand and wrist, comprising of 14 phalanges, 5 metacarpal bones and 8 carpal bones (Figure 1).

Figure 1: Skeletal structure of the hand and wrist (palmar view)

(from Kapit and Elson, 1977)
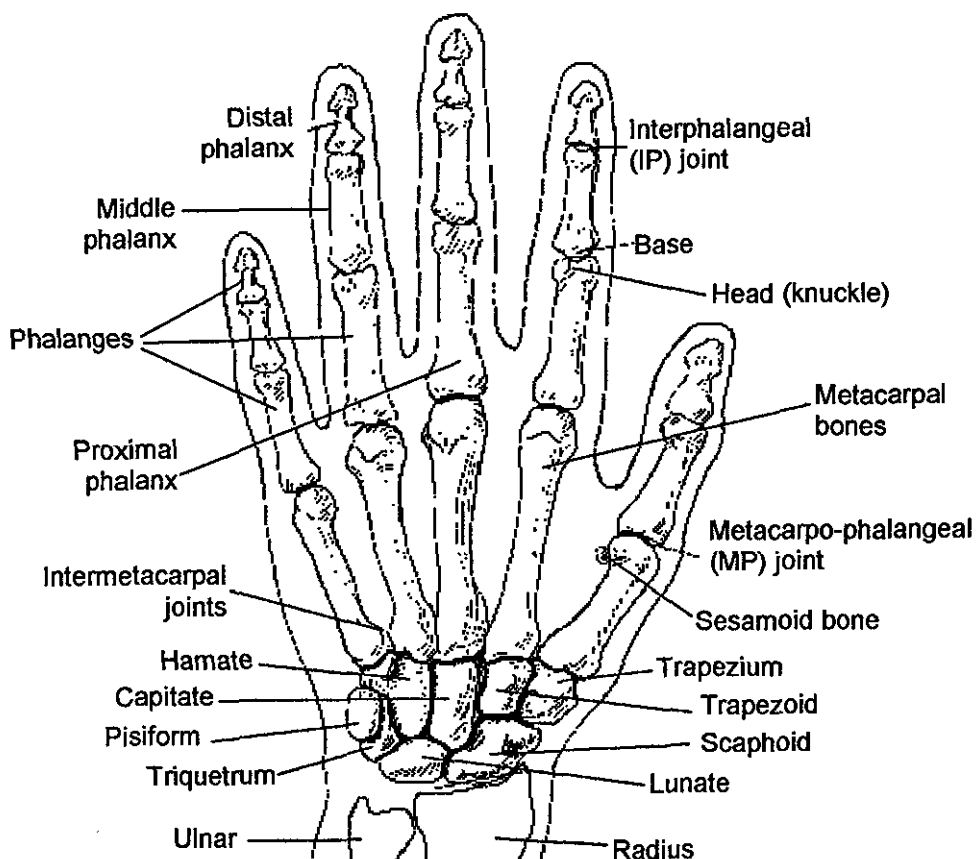
Muscles are attached to the skeleton by tendons. Most of the muscles that operate the hand are found in the forearm. Consequently, there are long tendons running from the forearm muscles to the bones in the hand (Figure 2). As these muscles contract to bend the fingers, the tendons slide through the wrist. These tendons are protected by synovial sheaths, which contain fluid to aid lubrication.

Figure 2: <u>Soft-tissue structures of the hand</u>

(from Hitchcock and D'Silva, 1995)
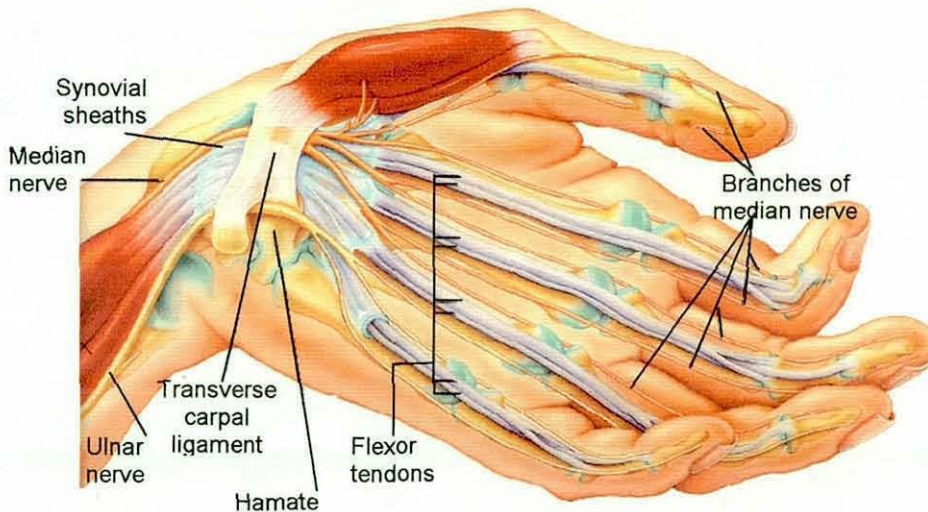
Three nerves, radial, median and ulnar, named with reference to their anatomical location, also pass through the wrist. Each of these nerves provides motor and sensory function to a specific area of the hand. The radial nerve is directed toward the proximal edge of the thumb. The median nerve serves 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.

Three branches of the median nerve develop within or just distal to the wrist. The recurrent thenar motor branch provides motor control to the thenar eminence. Digital nerve endings provide sensory function to the ulnar side of the first through third digits, and the radial side of the second through fourth digits. Finally, anastomotic fibers provide communication between the median and ulnar digital sensory distribution (Figure 3).

Figure 3: <u>Distal branches of the median nerve</u>

(from Rosenbaum and Ochoa, 1993)
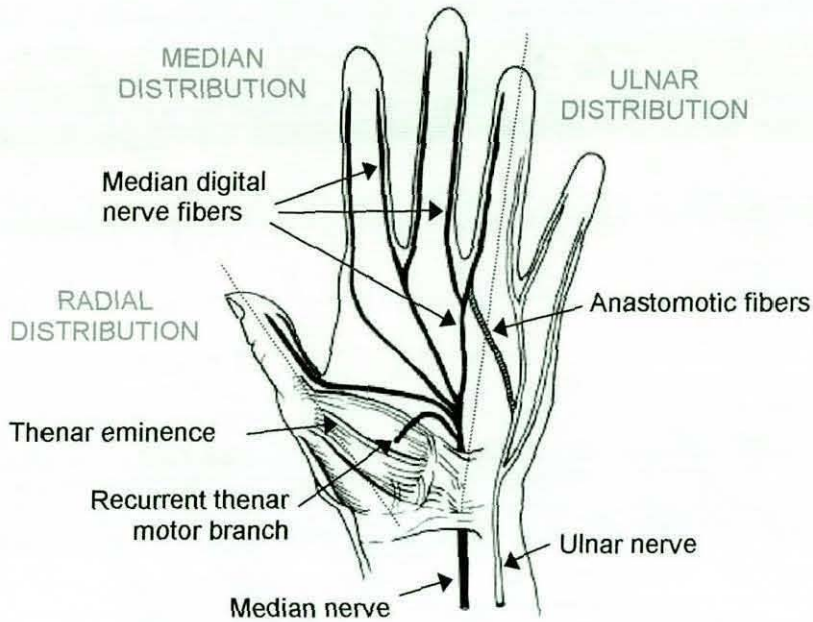
2.2.2 Anatomy of the Carpal Tunnel

The carpal tunnel is an anatomic space in the wrist bound on the palmar side by the inelastic transverse carpal ligament (flexor retinaculum), bridged between the scaphoid and hamate, and on the dorsal aspect by the eight carpal bones of the wrist. The ten structures that pass through the carpal tunnel include the four tendons of the flexor digitorum superficialis, the four tendons of the flexor digitorum profundus, the flexor pollicis longus and the median nerve (Figure 4).

Figure 4: <u>Cross section of the carpal tunnel</u>

(from Hitchcock and D'Silva, 1995)
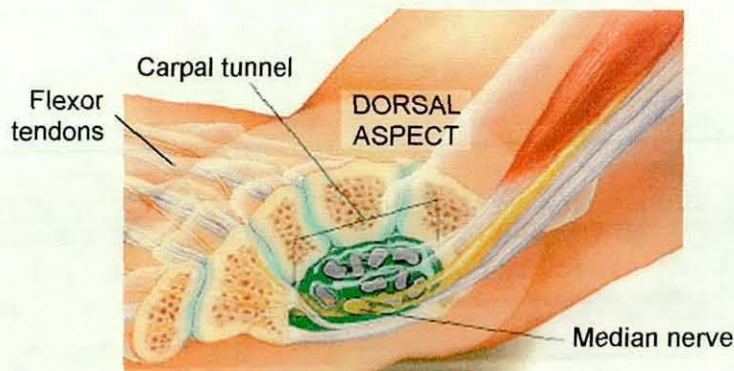
Cross-sectional area of the carpal tunnel is smallest 2.0 to 2.5 cm distal to the proximal entrance of the tunnel, where it is rigidly bound on three sides by a bony trough and bridged by the transverse carpal ligament (Robbins, 1963). It is at this site that the majority of median nerve neuropathies develop.

Using magnetic resonance imaging (MRI), Horch et al (1997) discovered that the cross-sectional area of the carpal tunnel was smaller in patients than in asymptomatic populations. Further, Cobb et al (1997) found the ratio of carpal tunnel contents to carpal tunnel volume to be greater in CTS patients compared to controls.

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 reduces its capacity or increases the volume of its contents can increase interstitial pressures (Cobb et al, 1992).

2.2.3 Carpal Tunnel Syndrome

First described in terms of its clinical manifestations by Sir James Paget in 1854, the term carpal tunnel syndrome (CTS) was first coined by Moersch in 1938. CTS is a clinical syndrome manifested by characteristic signs and symptoms resulting from an entrapment neuropathy of the median nerve at the wrist (Figure 5). If left untreated, CTS can lead to considerable discomfort, impaired function of the hand, and disability. It is the most common example of a nerve compression disorder (Slater, 1999), affecting between three and five percent of the general population (Atroshi et al, 1999).

In CTS, a pathophysiologic reaction to presented personal and/or physical risk factors can cause an increase in the volume of the contents of the carpal tunnel, which increases interstitial pressures. When pressures on the microvascular vessels within the median nerve rise above a critical threshold, venous obstruction causes capillary blood flow to be reduced below the level required for nerve viability. The resulting metabolic consequences of lack of nutrients and oxygen cause nerve conduction disturbances and symptoms associated with neurological impairment.

Figure 5: <u>Cross-section of a wrist with CTS</u>

(from Hitchcock and D'Silva, 1995)

Carpal bones:
1. Trapezium
2. Trapezoid
3. Capitate
4. Hamate

POSTERIOR

Flexor tendons

Swollen synovium of tendons

Compressed median nerve

Carpal tunnel

Flexor tendon in synovium

ANTERIOR Transverse carpal ligament
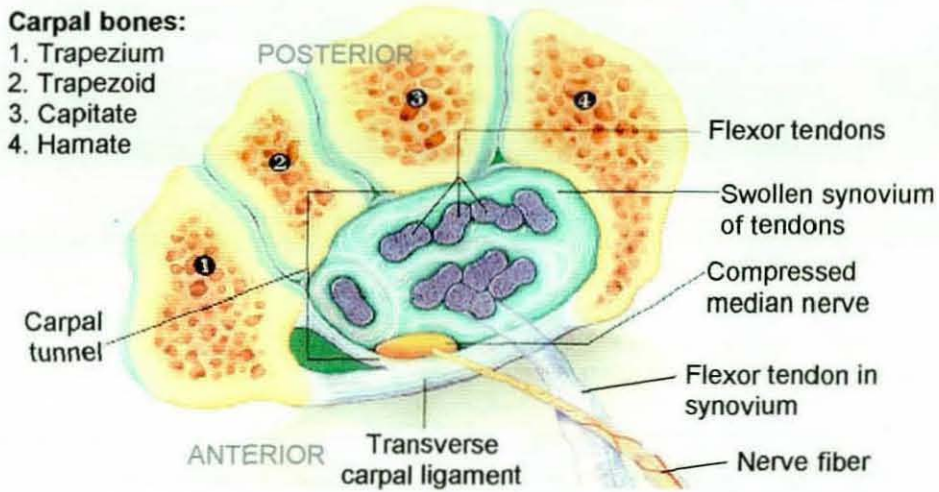
Nerve fiber

2.2.4 The Median Nerve

A peripheral nerve, such as the median, is a complex structure consisting of three major tissues: nerve fibers (axons with attached sensory and motor endings), connective tissue, including the myelin sheath, and a vascular plexus (Figure 6). The three major tissue types comprising the median nerve respond differently to trauma. Cumulative trauma can increase nerve pressure, reduce microcirculation and produce edema, resulting in local nerve ischemia (Pfalzer and McPhee, 1995).

Figure 6: <u>Anatomy of the median nerve</u>

(from Hitchcock and D'Silva, 1995)

Epineurium

Vascular plexus

Basal lamina

Endoneurium

Degenerated myelin sheath (Perineurium)

Normal myelin sheath

Axon of nerve

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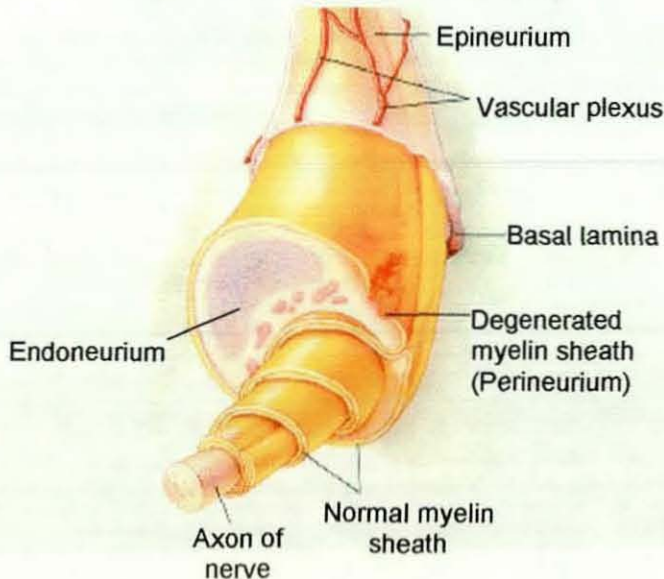
During periods of ischemia, sensory nerve function deteriorates. Inhibitory responses include a reduction of nerve threshold and excitability, altered recovery cycle and a progressive reduction of the magnitude and duration of the super normal period (the recovery phase following action potential). Conduction velocity becomes progressively slower, most likely due to reduced conduction of action potentials in the fastest conducting fibers (Stohr, 1980).

2.2.4.1 Nerve Fibers

Sensory type A fibers are large myelinated fibers that relay impulses associated with pressure, touch, temperature, muscle tension and joint position. These large nerve fascicles are more sensitive to ischemia than smaller ones, where trauma produces edema in the nerve trunk, causing accumulation of organelles and demyelination, leading to increased endoneurial fluid pressure. This pressure can affect microcirculation within the nerve fiber (Korthals et al, 1978).

Individual nerve fibers are able to maintain normal function, even under high pressures, as long as an adequate supply of oxygen is present (Grundfest, 1936). However, when pressures on the microvascular vessels within the median nerve rise above a critical threshold, venous obstruction causes capillary blood flow to be reduced below the level required for nerve viability (Szabo, 1998). The resulting metabolic consequences of lack of nutrients and oxygen cause axon degeneration (Pease et al, 1990; Seror, 1996), which produces nerve conduction disturbances and symptoms of carpal tunnel syndrome.

2.2.4.2 Connective Tissue

Surrounding the nerve fibers are three successive layers of connective tissue that protect the fibers' continuity. The endoneurium is the innermost layer, the perineurium is the intermediate layer, and the epineurium is the outermost layer (Figure 6). The protective function of these tissue layers is essential, since the individual nerve fibers are extremely vulnerable to damage.

2.2.4.3 Microcirculation

Effective neural communication is highly dependent on an adequate local oxygen supply (Lundborg, 1970), which is provided via a complex microvascular system. In the upper arm, the median nerve receives its blood supply from the accompanying axillary and brachial arteries. The common pattern for the forearm is for the radial and ulnar arteries to supply the median nerve via multiple anastomotic branches that feed a very small artery, the median artery, which adjoins the anterior surface of the nerve. In the hand, the superficial arterial arch supplies blood to the median nerve via a capillary plexus. The nerve itself is well vascularized at all levels within the structure.

A prominent median artery of the forearm appears in embryological development and normally involutes before birth. In rare cases, it persists into adult life (Zeiss and Guilliam-Haidet, 1993). Between 2.2 and 4.4 percent of individuals (Luyendijk, 1986) have a more pronounced median artery of approximately 1.8mm diameter (Olave et al, 1997), which passes through the carpal tunnel alongside the median nerve. A persisting vessel may cause damage to the nerve due to compression or ischemia (Galassi et al, 1980).

The vascular plexus supplies the median nerve with blood, oxygen and nutrients essential for normal nerve function. Capillaries follow the nerve fibers longitudinally and enter the perineurium at oblique angles. Lundborg (1989) suggests that a rise in tissue pressure inside the nerve fascicles causes the capillaries to close like valves. Even small elevations in pressure are associated with reduced intrafascicular blood flow (Gelberman et al, 1981; Lundborg, 1982).

Sunderland (1976) suggested that the vascular mechanism of carpal tunnel syndrome occurs in three stages, beginning with venous congestion. Nerve edema that follows, results from anoxic damage to the capillary endothelium leading to impairment of both venous and arterial blood supplies.

Classic signs of axonal degeneration are observed during periods of peripheral nerve ischemia including disintegration of cellular elements of vessels and perineurium, phagocytosis of nerve fibers, proliferation of Schwann cells and regenerating nerve fibers (Chalk and Dyck, 1993). A study by Korthals and Wisnewski (1975) on experimental animal nerves concluded

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that following production of peripheral nerve ischemia, extensive pathological changes were observed in all cases. Moreover, morphologic changes of the ischemic nerve were produced without compression, stretching or manipulation of the nerve. It was surmised that the probable cause of severe nerve damage was prolonged ischemia due to endoneurial edema (Korthals et al, 1978).

2.3 Medical Evaluation and Diagnosis

2.3.1 Signs and Symptoms

Symptoms of carpal tunnel syndrome are usually experienced in the region of the hand served by the median nerve. That is, the first three and one half fingers on the palmer side, and distal nail regions of the first four fingers on the dorsal side of the hand (Figure 7).

Figure 7: Nerve distributions of the hand

(from Putz-Anderson, 1988)

- radial
- median
unshaded - ulnar
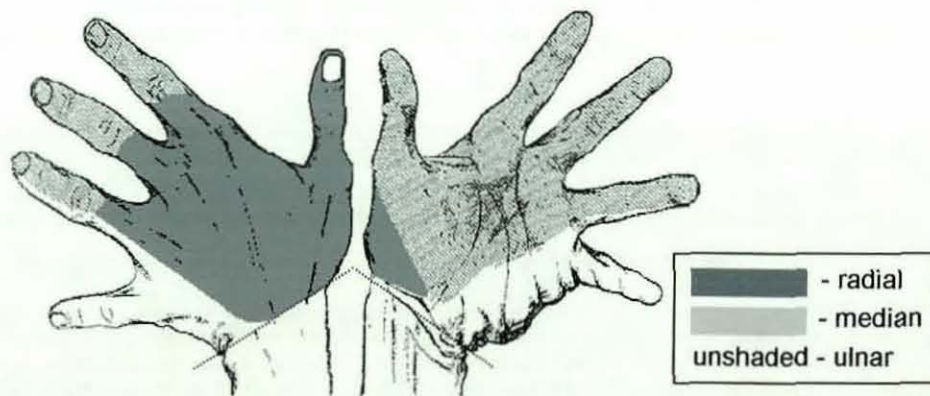
Acute carpal tunnel syndrome is often associated with nocturnal pain and tingling, episodic tingling and gradual numbness, all of which may be provoked by certain activities such as abnormal and static postures, repetitive and forceful hand motions.

As severity increases, a patient may experience constant aching, prickling and what has been described as 'painful numbness' in the fingers of the median distribution and deep in the palm. Perceptually, the patient may

recall subjective feelings of uselessness, mental sensation of swelling (although not apparent on inspection), clumsiness, and difficulty performing everyday tasks, such as unscrewing a bottle cap.

With the most severe cases of CTS, patients may experience dull aching throughout the limb, which radiates not only distal to the site of compression, but also proximally. Patients have reported pain throughout the forearm, upper arm, shoulder, and even into the neck. Changes in coloration of the skin are more apparent, especially with exposure to cold. There may be excessive sweating in the palm and a possible mild degree of edema. Wasting of the thenar muscle and mild weakness of the abductor pollicis brevis or opponens pollicis muscle may also be observed.

Carpal tunnel syndrome patients, at all levels of severity, also reported suffering from poor sleep quality, fragmentary sleep and sleepiness during the day due to the nocturnal exacerbation of their symptoms (Lehtinen et al 1996).

The prognostic value of subjective symptomatic experience in determining the severity of the syndrome has been shown to vary greatly based on the technique used to obtain such information. Solicitation via unstructured discussion with the patient has been shown to correlate poorly (40%) with clinically confirmed findings (Ferry et al, 1998a). Both sensitivity and reliability of findings increase considerably (62%) with the utilization of structured disease-specific questionnaire assessment tools (Atroshi et al, 1998; Bessette et al, 1998).

2.3.2 Clinical Diagnosis of Carpal Tunnel Syndrome

Due to the nature of nerve disorders, such as carpal tunnel syndrome, patients for whom symptomatic experience is similar may be suffering from different disorders masquerading as CTS, or from neurological irritation at unique sites along the same nerve length. Confidence in diagnostic findings is imperative before prescribing appropriate treatment, surgical or otherwise. There are many diagnostic utilities available to facilitate this process. A full diagnosis contains several parts:

History and Interview. The first and most important information is the patient's experience (Bland, 2000). How the problem started, how it has progressed, and what activities provoke symptomatic trauma. This information may be solicited through either structured questionnaire, interview techniques, or if time permits, both. By entering into discussion with the patient it may be possible to determine which activities appear to be restrictive or painful and thereby begin to classify the severity of nerve conduction abnormality.

Physical Examination. A complete evaluation requires specific examination of the affected body part. Many tests have been developed to evoke symptoms of carpal tunnel syndrome, including: Phalen's test, Tinel's test, Reverse Phalen's maneuver, pronator compression test, Allen's test, Adson's test, tethered median nerve stress test, range of motion, strength, vibratory sensory testing, and circulation/pulse testing. Several of the more widely used provocative evaluation techniques are described below.

2.3.2.1 Phalen's Test

During Phalen's test, pressure is exerted on the median nerve between the transverse carpal ligament and flexor tendons in the carpal tunnel by hyperflexing the wrist (Phalen and Kendrick, 1957). Depending on variations of the test, hyperflexion may be assisted or passive. Wrist posture is maintained for 60 seconds. Positive finding of paresthesia, radiating into the median distribution of the hand is usually apparent after a threshold of severity is attained. Phalen's test has been demonstrated to be 61% sensitive and 83% specific to carpal tunnel syndrome, especially in patients with somewhat severe or extreme symptoms (Tetro et al, 1998).

2.3.2.2 Reverse Phalen's Maneuver

Werner et al (1994a) investigated a variation on the original Phalen's test. Dubbed Reverse Phalen's maneuver, this modified technique involves assisted wrist and finger extension, which is maintained for 1 minute. Pain, numbness or paresthesia radiating distally throughout the median distribution of the hand and wrist is indicative of a positive finding.

A series of evaluations were performed by the developers to compare the standard and reverse Phalen's tests, including measures of intracarpal canal hydrostatic pressures (after Gelberman et al, 1981), the results of which were significantly higher for the modified technique.

2.3.2.3 Tinel's Test

Tinel's test is usually performed secondary to Phalen's test, since it has been found to produce an unacceptably high number of false positive results in asymptomatic candidates. Percussion of the median nerve at the anterior wrist produces positive findings of paresthesia in the median distribution. Phalen (1966) found this provocative test to be sensitive in 73% of CTS patients, but with poor specificity.

2.3.2.4 Pronator Compression Test

This test is similar to, though more aggressive than the Tourniquet test, in which forearm ischemia provokes symptoms of carpal tunnel syndrome. Patients with positive findings experience paresthesia and sensory loss in the median distribution of the hand. Gellman et al (1986) and Williams et al (1992) demonstrated a high sensitivity of this test in CTS patients within one minute of onset of ischemic provocation.

2.3.2.5 Tethered Median Nerve Stress Test (TMST)

The tethered median nerve stress test, developed by La Ban et al (1986), is performed by simultaneous hyperextension of the supinated wrist and the distal interphalangeal joint of the index finger for a period of one minute. The resultant tension in the median nerve invokes a positive pain recording in patients with chronic CTS. Raudino (2000) and Kaul et al (2000) demonstrated the lack of predictive power of this test in all but severe cases of CTS.

2.3.2.6 Vibration Threshold

Implications of vasosensory imbalance caused by compression of a nerve along its path form the basis of this diagnostic utility. However, compression at any site along the nerve path, including the carpal tunnel, will produce the same findings. A positive result therefore only suggests vasosensory imbalance, and does not necessarily preclude other disorders of the peripheral median nerve.

As a direct result of prolonged compression, the large myelinated fibers in the median palmar distribution are reduced in number. Abnormalities in the axon population should therefore be reflected in sensation to vibration stimuli. The frequency at which vibratory perception threshold of the median innervated index finger detected by the patient is compared with the ulnar innervated ipsilateral fourth digit threshold. Findings of this test have been shown to correlate accurately with symptoms of nerve compression.

Each of the above provocative tests for carpal tunnel syndrome evokes a subjective response from the patient with varying sensitivity and specificity. As such, they should not be interpreted as unequivocal diagnoses, but rather as tools to aid in the assessment of the patient's condition.

Based upon independent meta-analyses, D'Arcy and McGee (2000) and Massy-Westrop et al (2000) found that most clinical tests for carpal tunnel syndrome have little or no individual diagnostic value. Using simple diagnostic algorithms for combined tests, Szabo et al (1999) and O'Gradaigh and Merry (2000) demonstrated that the diagnostic value of traditional tests could be improved, the resulting predictive power being comparable to nerve conduction studies.

The following objective diagnostic utilities are under development for use in carpal tunnel syndrome assessment.

2.3.2.7 Thermography

Liquid crystal thermography (LCT) is a technology that is sensitive in the detection of asymmetries in heat distribution. Herrick and Herrick (1987)

demonstrated that thermal patterns in CTS patients showed a decreased vascular heat emission pattern over the median nerve. Meanwhile, Meyers et al (1989) reported the sensitivity of LCT as an independent diagnostic utility to be poor compared with nerve conduction studies. Thermography may be efficacious for the differential diagnostic of carpal tunnel syndrome from other peripheral neuropathies (Figure 8).

Figure 8: Infra-red thermographic image of the hand

Note temperature difference between median and ulnar distributions
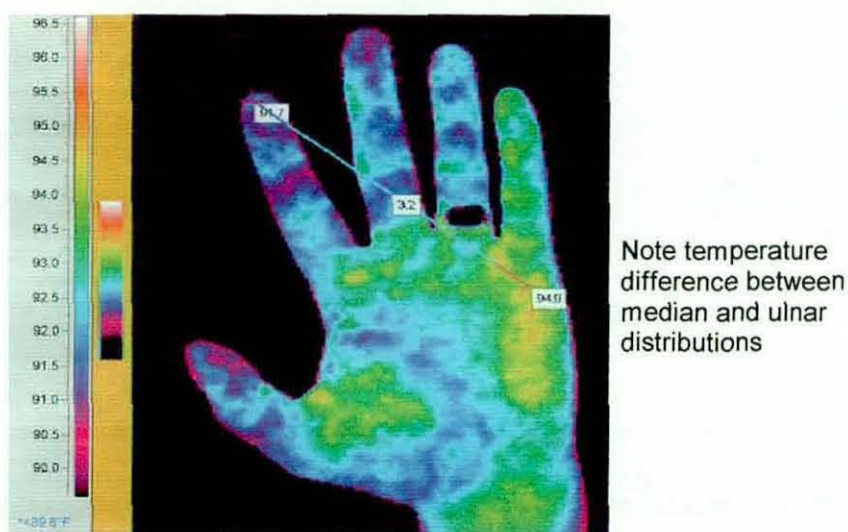
2.3.2.8 Computer Axial Tomography

Prior to the introduction of computerized technology, the only option available to the clinician when the source of discomfort was not apparent was surgical exploration. Armstrong and Chaffin (1979a) investigated alternatives to this procedure, but were unable to find any reliable association between external measures of hand shape, wrist circumference or body weight and prediction of cross-sectional area of the carpal tunnel.

Computerized tomography (CT) is a technology that may be used to measure the cross-sectional area of the carpal tunnel without the need for invasive surgery. Measures that can be determined using this method include: circumference and area of the carpal tunnel at each level, depth of the median nerve, width of the canal, and the thickness of transverse carpal ligament.

By calculating internal measures, computerized tomography can be used to accurately reveal space-occupying structures within the carpal tunnel

not obvious by external examination, such as accumulations of fat, muscle insertion within the canal, or skeletal abnormalities.

2.3.2.9 Magnetic Resonance Imaging

Magnetic Resonance Imaging (MRI) is a sensitive clinical tool that may be useful in identifying contributory physiological abnormalities, such as a persistent median artery (Lavey and Pearl, 1981), or evident pathological changes within the carpal tunnel, such as retinacular bowing, median nerve flattening and deep palmar bursitis (Radack et al, 1997; Monagle et al, 1999; Bonel et al, 2001). Both this technique and Computerized Tomography may be especially effective in cases where clinical signs are confusing as an alternative to painful and costly exploratory surgery (Brahme et al, 1997).

2.4 Electrodiagnostic Evaluation of the Median Nerve

At this time the most reliable technique for assessing the severity of median neuropathy in carpal tunnel syndrome is the electroneurological evaluation (Ghavanini and Haghighat, 1998). Electroneurometers are used to objectively quantify nerve conduction velocity by measuring the time required for an impulse to travel from a stimulus to a more proximal or distal site at which a motor or sensory response is evoked (Figure 9).

Figure 9: Surface electrodiagnostic testing of the median nerve
(Medical Multimedia Group)

Electrodiagnositic testing has become widely instituted and is now the standard in diagnosing carpal tunnel syndrome and determining severity of median nerve involvement at the wrist (Ghavanini and Haghighat, 1998).

2.4.1 Development of Electrodiagnostic Techniques

Exploratory studies by Simpson and Carpendale (1956) demonstrated that motor distal latencies (MDLs) are prolonged in carpal tunnel syndrome patients. Although the first diagnostic techniques were poorly standardized, they were able to show positive findings in a group of CTS patients with advanced neurological impairment. This first result was a landmark discovery in the objective evaluation of peripheral nerve disorders.

Early nerve conduction studies used anatomic landmarks, such as the distal and proximal wrist creases as reference marks for probe placements. The distance over which motor impulses were transmitted differed significantly as a function of hand anthropometry. The range of measured motor distal latencies was therefore relatively great and upper limits (mean + 2 standard deviations) relatively long. The sensitivity of early electrodiagnostic tests was thus quite poor.

Additionally, in order to accurately record the involuntary motor response time with repeatability, clinicians would insert electromyography (EMG) needles into the palmar muscles to monitor motor response. Since anesthesia might confound findings, it was avoided during this procedure, which was painful for the patient.

2.4.2 Standardization of Measures

Melvin, Schuchmann and Lanese (1973) introduced standardization of impulse distance, irrespective of hand size, thereby demonstrating a significant reduction in the standard deviation of measures. The upper limit of normal for measures was proportionately reduced, significantly improving the sensitivity of electrodiagnostic testing. Buchthal, Rosenfalck and Trojaborg

(1974) confirmed this important discovery, with their determination that median motor distal latencies increased with increasing distance of conduction.

The importance of nerve conduction velocity measures in the diagnosis of nerve disorders gained momentum. Improvements in techniques and instrumentation including supramaximal stimulation, standardized placement of electrodes, consistent latency distance, standardization of amplifier gain, and control of skin temperature have enabled electromyographers to acquire more accurate results about the function of peripheral nerves.

Technological improvements now permit the use of surface electrodes rather than needle probes. This development has significantly improved patients' tolerance for the technology without affecting the reliability of the findings (Smith, 1998). Although still an uncomfortable experience due to the involuntary response to the supramaximal stimulation, nerve conduction velocity measures may be used as a clinical research technique to quantify the functional status of peripheral nerves.

2.4.3 Mathematical Refinement of the Technology

As the variability of nerve conduction is minimized, the standard deviation of measures should be proportionately reduced and normal ranges narrowed. With each improvement in technique or technology, the sensitivity of measures for early detection of mild carpal tunnel syndrome increases. Efforts in this area will be most rewarding, since it is through early diagnosis or better prevention that pain and suffering, associated costs and lost worktime will be substantially reduced.

2.4.4 Motor versus Sensory Studies

A mixed nerve such as the median carries both motor and sensory fibers. Each type of fiber has a different conduction velocity. In a clinical context, it is often important to have an independent assessment of the two.

Motor fibers can be isolated by selectively recording from the appropriate muscle. Selectively stimulating or recording from a sensory nerve or distal sensory branch is used to isolate sensory fibers.

When performing motor studies, the latency of the motor response is not the result of nerve conduction alone. To avoid this problem, two sites may be used, between which the true motor response is calculated. Sensory studies involve nerve action potentials rather than compound muscle potentials, therefore only one stimulation site is necessary and latencies reflect true neural conduction times. Sensory measures are both a more direct measure of nerve function and more sensitive to changes in nerve function.

2.4.5 Sensory Nerve Conduction Velocity

There are two different methods for determining sensory nerve conduction velocity (SNCV); orthodromic and antidromic. In orthodromic studies, the sensory distal branch of a nerve is stimulated while recording is made more proximal over the nerve. The direction of conduction is the same as it would be under physiologic circumstances. Sensory nerve action potentials (SNAP) are less clearly visible, compared with antidromic measures, because the amplitudes of the potentials are lower (Rosenberger and Bittenbring, 1976). In antidromic studies, the nerve is stimulated proximally and the sensory nerve action potential recorded in the distal sensory branch. In either case, the distance (D) is measured from the stimulus cathode to the active recording electrode (Figure 10).

Figure 10: <u>Sensory nerve conduction velocity concept</u>
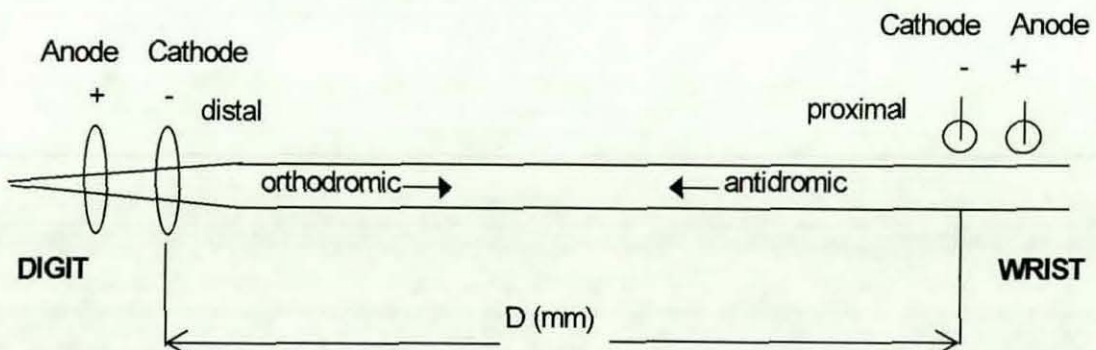
Recording from distal sensory fibers using the antidromic technique isolates the sensory response and is the more sensitive method for the diagnosis of mild carpal tunnel syndrome (Hildenhage et al, 1985).

Using the antidromic technique, Macdonnel et al (1990) evaluated the sensitivity of digital nerve fibers in digits 2 through 4 in a group of 34 CTS patients with age and gender-matched controls. Their findings indicate that the middle finger (digit 3) is the most sensitive recording site for sensory antidromic studies.

Velocities can be calculated over any nerve length depending on the location of the stimulus, which may be applied at mixed fiber locations along the nerve. Modern non-invasive electrodiagnostic equipment use software algorithms to compute nerve function measures based on defined reference points along the nerve response waveform. An example sensory waveform is presented in Figure 11.

Figure 11: Normal median sensory waveform
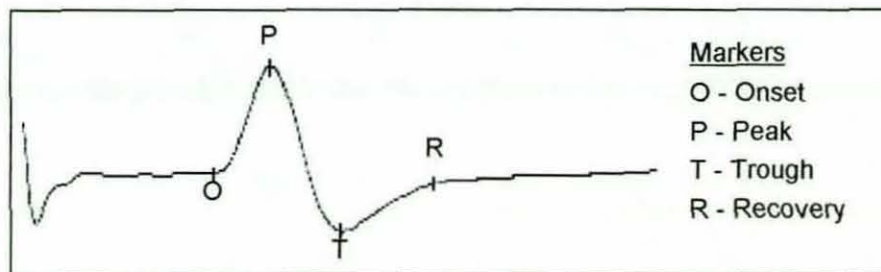
Typical measures of sensory nerve function include:

- *Onset latency* [O] (msec) - time between nerve stimulation and initial response detected at the active recording electrode.
- *Peak latency* [P] (msec) - time between nerve stimulation and peak response detected at the active recording electrode
- *Duration* [P-O: x axis] (msec) - time difference between onset and peak latencies
- *Amplitude* [P-O: y axis] (μV) - height of the waveform between peak and onset measures.
- *Area* (μVmsec) - area of the waveform described by the sensory response.
- *Conduction velocity* (ms^{-1}) - calculated by dividing stimulated nerve length by latency (peak latency is typically used for this measure).

2.4.6 Normal Values for Median Sensory Nerve Conduction

Reference values are necessary to distinguish between normal and abnormal nerve function. Based on large samples of the general population, normal would be defined under an unskewed Gaussian distribution curve as mean value ± 1 standard deviation. Empirical limits of normal are defined as mean ± 2 standard deviations. These ranges are based on optimal sensitivity and specificity of the measures, where reducing the range enhances ability to detect mild neuropathies but decreases predictive accuracy (Nathan et al, 1988a).

Three studies of antidromic median nerve conduction between the wrist and digit have been performed from which reference values were determined (Kimura, 1979; Carroll, 1987; Jackson and Clifford, 1989). Findings of the studies are comparable. The greater sensitivity for detecting abnormal sensory median nerve function in patients with carpal tunnel syndrome was demonstrated by Jackson and Clifford (1989) across a sample of 131 symptomatic and 38 asymptomatic hands.

Using a fixed distance of 140mm between the stimulus cathode and active recording electrode, and a minimum hand temperature of $31.0^{\circ}C$, Jackson and Clifford (1989) defined the following reference values (Table 1):

Table 1: Reference values for sensory median nerve function
(Jackson and Clifford, 1989)

Sensory Values	Normal	Abnormal
Onset latency	2.47 ± 0.12 msec	> 2.72 msec
Peak latency	3.16 ± 0.16 msec	> 3.48 msec
Conduction Velocity	44.30 ± 2.36 ms^{-1}	< 40.22 ms^{-1}

The severity of patient exposure may be determined with reasonable confidence from the collective interpretation of patient symptomatic, clinically provocative and electrodiagnostic findings (Table 2), from which an appropriate course of treatment may be prescribed.

Table 2: Summary of diagnostic criteria for carpal tunnel syndrome
(adapted from Rossier and Blair, 1984; Gross, 1988; Gupta and Benstead,
1997; Padua et al, 1997a)

Severity of Disorder	Subjective	Observational	Clinical	Electro-Neurological
Mild	Episodic tingling and gradual numbness in median distribution	Occasional nocturnal symptoms	Positive findings of Tinel's test	Abnormal sensory, but normal motor findings
Moderate	Aching, prickling and painful numbness	Some difficulty performing everyday tasks Nocturnal exacerbation	Positive reverse Phalen's test Positive pronator compression test	Abnormal sensory and abnormal motor findings
Severe	Dull aching radiating both distally and proximally	Changes in skin coloration Problems with dropping things Excessive sweating in affected area	Positive Phalen's test Reduced grip strength Thenar atrophy	Absence of sensory response Abnormal motor findings

2.4.7 Correction Factors for Electrodiagnostic Studies

Electrodiagnostic studies facilitate objective measurement of median nerve function. Personal characteristics have been found to influence normal limits of nerve conduction. Hence, a finding of abnormal median slowing may be a normal population variant after considering personal and anthropometric characteristics of the individual. It is therefore necessary to correct for normal physiologic changes in median nerve function to isolate pathologic changes responsible for nerve slowing.

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2.4.7.1 Skin Temperature

Changes in skin temperature present the greatest effect on median nerve function (Letz and Gerr, 1994; Yuassa et al, 1996), where skin temperature and nerve temperature are highly correlated (Halar et al, 1983). Nerve slowing of 1.4 - 2.3 ms^{-1} has been reported for each 1.0 degree Celsius decrease in near-nerve skin temperature (Halar et al, 1983; Stetson et al, 1993; Letz and Gerr, 1994). 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.

2.4.7.2 Age (Aging)

Slowing of median nerve function occurs naturally with increasing age though not necessarily leading to the development of CTS (Nathan et al, 1988b, 1992, 1998). Specifically, nerve conduction was found to decrease by 1.3 ms^{-1} per ten-year increase in age (Stetson et al, 1992; Letz and Gerr, 1994). Carroll (1987) applied similar correction factors in the development of age-range specific reference values for median electrophysiologic studies.

2.4.7.3 Gender

After correcting for other highly correlated personal and anthropometric characteristics, normal median nerve function is found to be undifferentiated between male and female populations (Nathan et al, 1988b, 1992; Stetson et al, 1992; Robinson et al, 1993).

2.4.7.4 Race

Letz and Gerr (1994) found there to be a small though statistically significant effect of race, where sensory median nerve conduction velocity

was 0.6 ms^{-1} slower across African-American subjects compared with a general population sample.

2.4.7.5 Height

Height has been negatively correlated with peripheral nerve conduction, such that each 100 mm increase in height induces conduction slowing of 0.12 - 0.17 ms^{-1} (Trojaborg et al, 1992; Stetson et al 1992; Letz and Gerr, 1994).

2.4.7.6 Body Mass Index (BMI)

Results of studies evaluating the effect of body mass index on median nerve conduction are conflicting. Nathan et al (1992) reported a strong positive correlation, whereas Letz and Gerr (1994) documented a small negative association between measures.

2.4.7.7 Alcohol Consumption and Tobacco Use

Effects of smoking and alcohol intake on nerve function are conflicting in the literature. Yuasa et al (1996) suggest that neither factor has a significant effect, while Letz and Gerr (1994) present a highly significant negative effect of smoking (-0.5ms^{-1}) and a positive association with alcohol consumption, the effect size of which is dependent on the quantity consumed.

2.5 Treatment Regimes and Success Rates

If carpal tunnel syndrome is detected during the early stages of development, conservative treatment is highly recommended. This can be significantly less disruptive to the patient and less costly than surgical alternatives. The patient may also be able to return to their normal duties within a relatively short time and with minimal discomfort. Carneiro (1999) discusses that the sensible management of CTS should be dictated by the cause.

Conservative non-surgical treatment of CTS combines four types of therapies. Restricting motion and splinting to immobilize the affected area; applying heat or cold to facilitate the repair process; medications and injections to reduce inflammation and pain; and special exercises to promote circulation.

A simple wrist brace will sometimes lessen symptoms of mild carpal tunnel syndrome. This is especially effective if the patient is instructed to refrain from activities that require working against the brace, which could otherwise accelerate the onset of more severe symptomology due to increased tendon forces. The brace might be worn at night to prevent awkward wrist postures during sleep, which are thought to exacerbate nocturnal symptomatic experience.

Nonsteroid anti-inflammatory drugs (NSAIDs) are used as the second line of conservative non-surgical treatment. An injection into the carpal tunnel may be prescribed to decrease swelling of tissue structures, thereby permitting opportunity for recovery. Giannini et al. (1991) showed that local steroid injection facilitated improvement in median nerve function long after the pharmacological effects of the agents dissipated. A study by Chang et al (1998) demonstrated that of four common corticosteroid treatments, prednisolone proved most effective in mild to moderate cases of CTS.

Boniface et al (1994) and Rozmaryn et al (1998) concur that a significant number of CTS cases (70-86%) may be resolved without surgical intervention. Only if the severity of symptoms is extreme, defined as peak latency 1.0 msec greater than mean value, or conduction velocity 10 ms^{-1} slower than mean (Higgs et al, 1997), and conservative treatments are ineffective, should surgical means of rehabilitation be considered (Slater, 1999).

Traditional release surgery involves the making of a small incision, usually less than two inches, along the palm of the hand. This incision is continued through the palmar fascia to reveal the transverse carpal ligament, the constricting element. The transverse carpal ligament is then cut to relieve pressure from the median nerve (Figure 12). Only the skin incision is sutured, leaving the gap in the transverse carpal ligament to heal naturally.

Figure 12: <u>Surgical release of median nerve pressure at the carpal tunnel</u>

(From Phalen, 1966)

Improvements in surgical techniques now permit the surgeon to use endoscopic tools for this procedure. Either one or two ports may be cut, depending upon the preferred variation, through which both monitoring and dissection are accomplished. Although endoscopic surgeries tend to be more expensive, and less successful than the traditional approach, especially in persistent or recurrent cases (Forman et al, 1998), the reported benefits include: decreased surgical time, decreased post-operative attention, early return to duty, decreased pain, and increased thenar strength (Bernstein, 1994).

Since thinner nerve fibers recover faster than do thicker fibers (Nygaard et al, 1996), post-operative recovery following myofascial release surgery is often dependent on the degree of pre-operative impairment (Rosen et al, 1997) and duration of symptoms (Choi and Ahn, 1998). Pre-operative electrophysiological assessment of median nerve function may be used to predict surgical outcome (Padua et al, 1996, 1997b).

In a prospective study, Aulisa et al (1998) observed complete clinical and electrophysiological recovery following surgical decompression only in patients with mild cases of CTS. Further, DeStefano et al (1997) discovered that patients who had surgery three or more years after initial onset were less likely to experience complete symptomatic resolution than those who had surgery during earlier development of the condition.

A new treatment technique using laser neurolysis to effect biological changes in photosensitive fibers of the median nerve presents encouraging preliminary findings, where the syndrome was corrected in 77 percent of thirty cases (Weintraub, 1997). This approach is both more cost-effective and less traumatic than surgical decompression and may play a role in the future management of carpal tunnel syndrome.

Several studies support aggressive post-operative rehabilitation therapy and early return to work if effective recovery is to be achieved. One cost-effective approach might be to teach self-stretching exercises to patients of myofascial release surgery, which has been shown to reduce symptoms and improve electrophysiologic results (Sucher, 1993). In a comparative evaluation, Goodman (1992) demonstrated that fourteen percent of a traditional treatment group while only two-percent of an aggressive return-to-work group failed to resume their normal duties following carpal tunnel release surgery. Furthermore, tangible costs were found to be fifty percent lower in the aggressively treated group.

If a complete and permanent recovery is expected, it is important that the worker not be returned to the same job or task that precipitated the disorder without a thorough ergonomic assessment of the worksite. Appropriate engineering and administrative controls should be implemented to minimize the risk of re-injury.

2.5.1 Recurrence of Carpal Tunnel Syndrome

Recurrences of the syndrome following surgery are often due to inadequacies of the first procedure, such as incomplete splitting of the transverse carpal ligament in the endoscopic technique (Lee et al, 1992; Forman et al, 1998), or compression of the median nerve caused by excessive and improperly formed scar tissue. Up to fifty percent of recurrent patients may have confounding medical conditions, such as insulin-dependent diabetes mellitus, terminal renal insufficiency, or acromegaly, which increase their susceptibility to nerve disorders (Kern et al., 1993). Patients with carpal

tunnel syndrome secondary to a systemic disease are particularly at risk for recurrent symptoms.

2.6 Incidence Work-Related Musculoskeletal Disorders

Few publications have been prepared on incidence pertaining to work-related carpal tunnel syndrome. Data from the U.S. Department of Labor, Bureau of Labor Statistics (US DoL BLS) is the most complete of all sources, including governmental agencies from the United States, European and Austalasian countries, and non-governmental sources, such as insurance companies.

The reliability of incidence data from the Bureau of Labor Statistics is however compromised. Prior to 1992, reporting of carpal tunnel syndrome incidence was grouped with other repetitive motion disorders, including cumulative hearing loss and Raynaud's phenomenon. Furthermore, dependability of the data may be jeopardized due to under-reporting (Fine et al, 1986) organizational, political or social influence, and/or misdiagnosis and misclassification. A selective loss of symptomatic employees may also occur in high-risk jobs, a form of healthy-worker effect (Morgenstern et al, 1991). With appropriate consideration given to these limitations of the data, the incidence of work-related carpal tunnel syndrome is presented.

2.6.1 Incidence of Work-Related Carpal Tunnel Syndrome in the US

The U.S. Department of Labor, Bureau of Labor statistics defined repetitive trauma disorders for the purpose of classifying work-related incidence of these occupational illnesses to include:

"...conditions due to repeated motion, vibration, or pressure, such as carpal tunnel syndrome; noise-induced hearing loss; synovitis; tenosynovitis and bursitis; and Raynaud's phenomenon." (US Department of Labor, 1988).

Although repetitive motion disorders represent only a small percentage of total occupational injuries and illnesses in the U.S. (1999 = 4.0% of the 5.7 million total; US Department of Labor, 2000), group classification has limited the analysis of incidence for individual disorders. The following graph (Figure 13) illustrates the increase in repetitive motion disorders presented as a percentage of total occupational illnesses during the past 19 years.

Figure 13: Disorders associated with repetitive motion as a percentage of total occupational illnesses in private industry
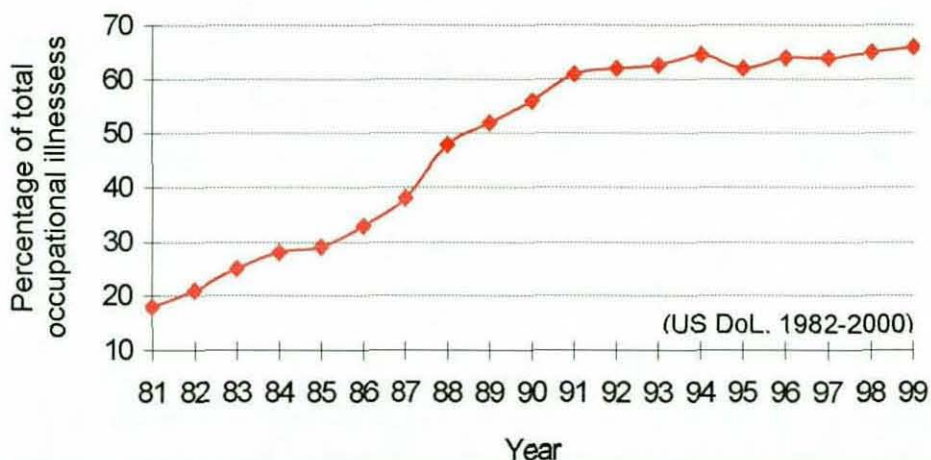
From 1981 through 1990, there was a marked increase in reporting of work-related repetitive trauma disorders, with an accelerated increase during 1987 and 1988. Brogmus, Webster and Sorock (1994) presented several theories on escalated reporting of work-related incidence, which are listed in the following order of importance:
a) Increased awareness by employees and medical practitioners through media attention and employer training programs
b) Increased productivity demands due to manufacturing automation
c) Increased reliance on computer terminals in the workplace
d) Improved reporting and classification procedures
e) Gradual aging of the US workforce population, and
f) Growing proportion of women in the workplace.

Presented as a percentage of occupational illnesses (Figure 13), the reporting of work-related repetitive motion disorders appears to have remained consistent since 1993. In fact, when reported as the actual number

of cases (Figure 14), a decline in the reporting of both occupational illnesses and repetitive motion disorders is noted during the period since 1994.

Figure 14: Number of reported occupational illnesses and repetitive trauma cases in private industry, by year
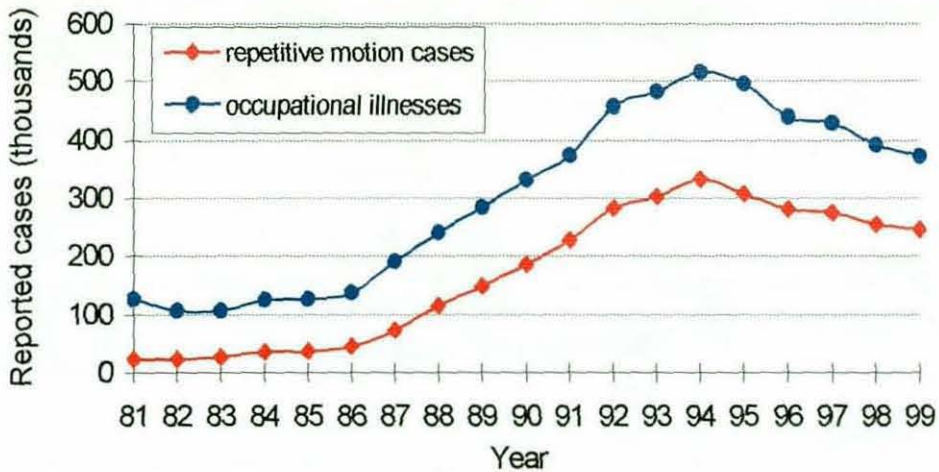
When presented as a percent change in reporting based on previous year statistics, the epidemic reporting of disorders associated with repeated trauma actually began to decline after 1988 and has been more favorable since (Figure 3). It is speculated that the reduced incidence in the workplace is in part due to successful ergonomic interventions within specific high-risk trades, such as the meat industry, where incidence fell by 15.9% following institution of comprehensive intervention programs (MacLeod, 1996).

Figure 15: Percent change in reporting of disorders associated with repeated trauma based on previous year statistics
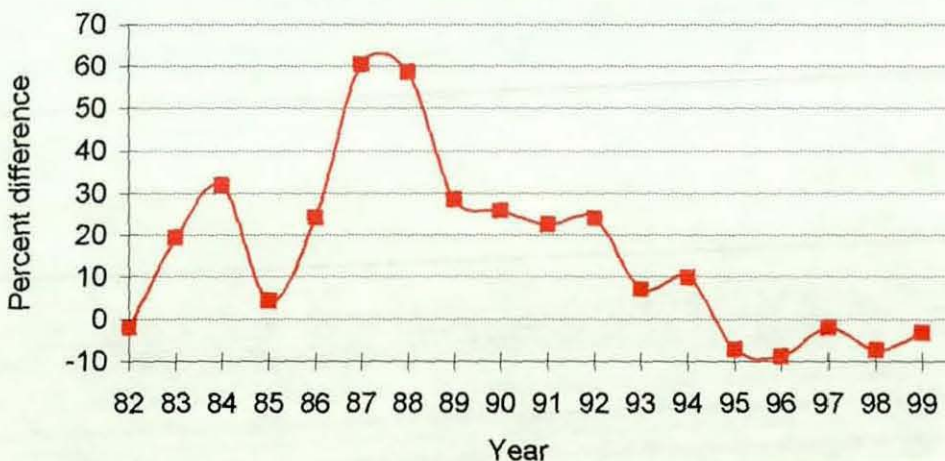
The Bureau of Labor Statistics redesigned their survey in 1992 to report, for the first time, the diagnosis of specific repetitive motion disorders, including work-related carpal tunnel syndrome, that commonly affect the upper extremity. The limited data from 1992 to 1999 (most current US DoL data) suggests that incidence of CTS involving lost workdays is approximately 34 percent of all occupational illnesses (Table 3).

Table 3: Work-related incidence of carpal tunnel syndrome

(US Department of Labor, 1994-2000)

	1992	1993	1994	1995	1996	1997	1998	1999
Number CTS cases	33,000	41,019	38,337	31,457	29,937	29,244	26,266	27,922
% Illnesses (lost workday)	31.4	35.1	32.7	29.5	31.6	33.7	32.1	na*
Men %	34.0	31.0	29.0	28.4	30.7	29.2	28.6	32.9
Women %	66.0	69.0	71.0	71.6	69.3	70.8	71.4	66.8
Manufacturing	56	41.5	42.4	42.8	40.2	39.2	40.7	38.5
Trade %	15	16.7	19.1	19.0	20.1	16.9	15.3	16.6
Services %	na*	8.3	7.2	6.7	7.9	9.7	7.5	8.4
Administrative	na*	35.6	35.5	37.1	38.5	37.7	38.2	35.7

* not available

Data indicate that females are twice as likely to report work-related incidence of carpal tunnel syndrome than are males. The majority (63.4%) of cases develop between the ages of 35 and 54 years, with more than one-third of all cases (35.8%) occurring between 35 and 44 years (US Department of Labor, 2000). These observations agree with the findings of Franklin et al (1991) and Martinez-Albaladejo et al (1993) that there appears to be a female predominance to the disorder and maximal incidence in the middle years. Martinez-Albaladejo et al further established that the average time for evolution of carpal tunnel syndrome is shorter for males (1.38 years) than females (2.4 years).

Approximately forty percent of all WR-CTS cases involving lost workdays are attributable to manufacturing industries (US Department of

Labor, 1995-2000) (Table 3). Massive downsizing of manufacturing operations in favor of semi-automated processes has increased task and productivity demands at the individual operator level. Occupational incidence may be minimized through ergonomic intervention to optimize the relationship between task demands and operator capacity.

Second to cases of CTS attributable to manufacturing are administrative activities, which account for approximately thirty-six percent of all incidents involving lost workdays. It is suspected that the severity of office related cases of CTS might be somewhat milder than manufacturing cases, since office-based employees may be more likely to confront the problem earlier, as their skills are more easily transferable (Lantigua-Peterson, 1999).

The mean incidence rate for carpal tunnel syndrome involving lost workdays across US private sector industry during 1997 was 3.4 cases per 10,000 full-time employees. For the same period, manufacturing, trade, services and administrative industry divisions recorded incidence rates of 6.5, 2.0, 2.4 and 3.9, respectively (US Department of Labor, 1998). Only the manufacturing sector presents incidence statistics considerably higher than the norm.

2.7 Social and Economic Costs

From a functional and psychosocial perspective there are few conditions as disabling as those which affect the hand and wrist. Everyday activities become physically challenging due to diminished motor and sensory function of the hand. Psychological perceptions of frustration and poor self-motivation can and often arise out of the physical limitations experienced by carpal tunnel syndrome patients.

Economically, it is estimated that the burden of work-related carpal tunnel syndrome on U.S. industry exceeds nine billion dollars per year (US Department of Labor, 1999). Furthermore, Silverstein et al (1998) reported that average direct worker's compensation claim cost (medical treatment and indemnity) in the state of Washington pertaining to carpal tunnel syndrome

was $12,794 (median: $4190), making CTS cases three times more expensive than any typical occupational injury or illness claim.

A significant share of this expense is consumed by the costs of surgical treatment, which is estimated to be between $400 million and $500 million per year. A proportion of these surgeries are due to symptomatic recurrence where a patient's recovery is encumbered by a prior deficient procedure (Kern et al, 1993).

When determining the cost of worker injuries it is usual to sum obvious expenses associated with medical intervention and workers compensation insurance. However, as Figure 16 below suggests, the total injury costs might be as much as five times the direct costs. The profound economic impact of this trend is reflected by the staggering sum of escalating tangible and intangible costs associated with its management (Rayan, 1999).

Figure 16: Direct and indirect costs associated with CTD incidence.
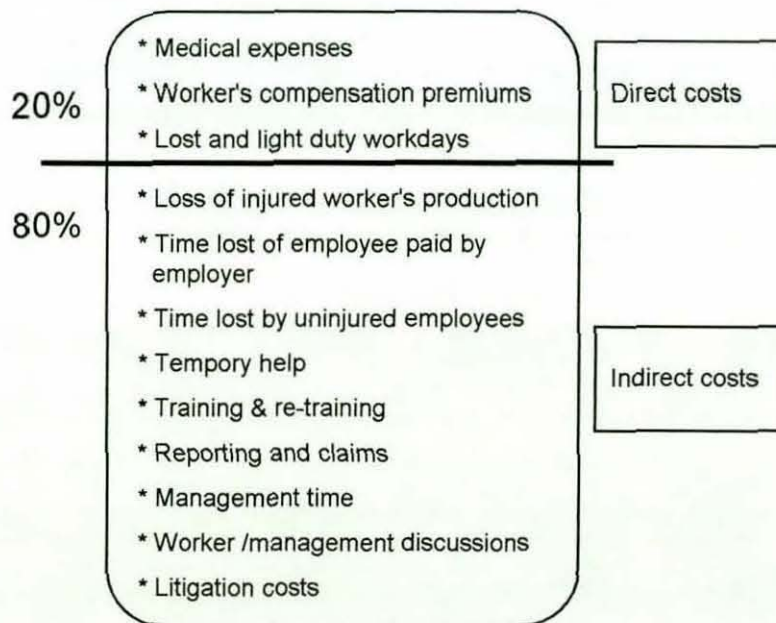
Cases of carpal tunnel syndrome also have the longest recuperation period of any reported occupational injury or illness, even higher than extremity amputations. More than 33 percent of work-related CTS cases involve greater than one month lost work time, with a median recovery period of 15 days, compared to the overall median for occupational injuries and illnesses of 6 days (US Department of Labor, 1999).

CHAPTER 3: AETIOLOGY OF CARPAL TUNNEL SYNDROME

The aetiology of carpal tunnel syndrome is complex. Epidemiological studies have identified significant relationships between health outcomes and a multiplicity of both personal and occupational risk factors. Occupational factors include high task repetition, forceful exertions, awkward postures, mechanical contact stresses, exposure to vibration, exposure to low temperatures, and work organization (Armstrong et al., 1986; Armstrong et al., 1993; Hagberg et al., 1995). Personal risk factors include age, gender, previous trauma, anthropometry, certain medical conditions, nutrition, and lifestyle factors (Nathan et al, 1994; Pfalzer and McPhee, 1995).

Figure 17 outlines a conceptual framework, indicating the roles that various risk factors may play in the development of carpal tunnel syndrome. Such factors may include personal, physical, psychological, social and organizational elements. The balance between imposed stressors and opportunity for recovery describes the potential for change in health status.

Figure 17: Risk factors associated with carpal tunnel syndrome
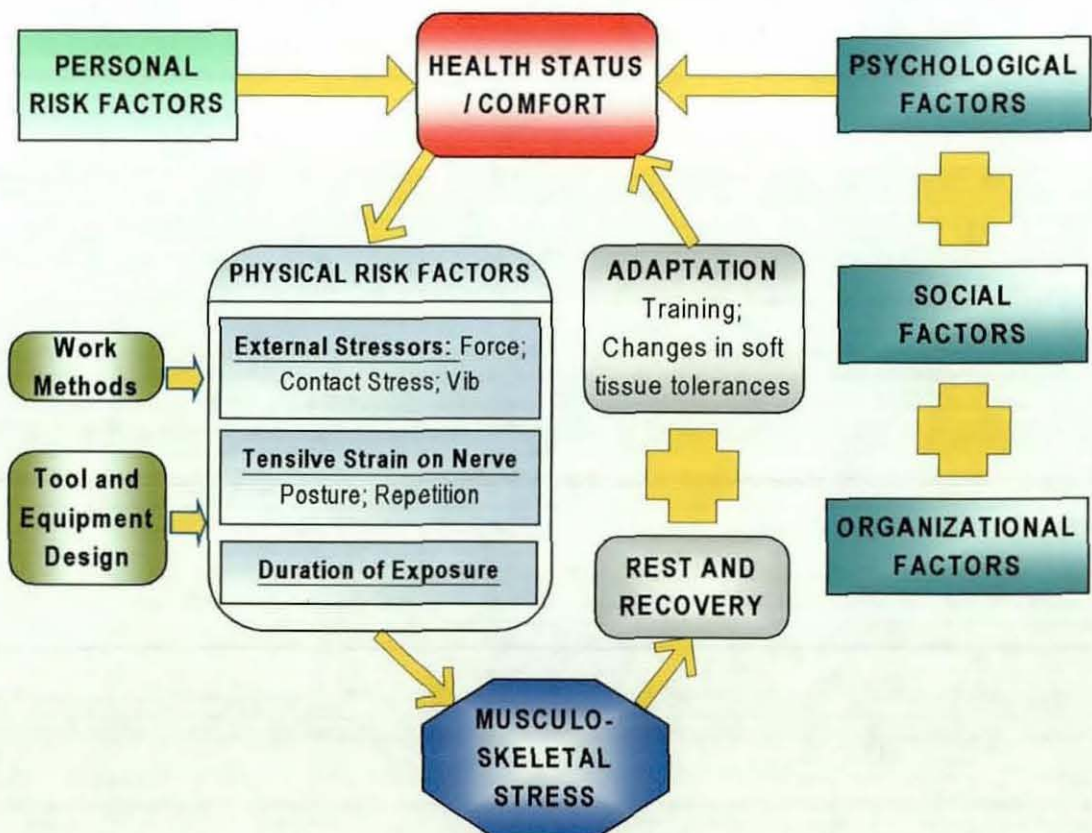
It has been shown that the prevalence of CTS increases with exposure to certain risk factors. However, it is not known at what level the risk becomes significantly elevated for a single factor or combination of factors. The following discussion will focus on the state of the science with regard to present understanding of contributing physical and personal factors in the development of carpal tunnel syndrome.

3.1 Occupational Risk Factors

The relationships among physical risk factors and responses of the musculoskeletal system have been studied extensively. Data from cadaver and animal studies have shown that while soft tissue structures, including muscle, tendon, ligament and nerve can tolerate certain loads, sufficient acute or cumulative loading can lead to failure. Even at levels of force below the failure level there is scientific evidence that deformation can produce inflammation, failure at microscopic levels and muscle fatigue.

Physical risk factors can be both occupational and non-occupational, such as those presented by recreational pursuits. The following review shall focus on workplace risk factors. However, many elements discussed may also be applicable to certain leisure activities.

3.1.1 Epidemiological Evidence

In a meta-analysis of epidemiological studies pertaining to the work-relatedness of upper extremity musculoskeletal disorders, Stock (1991) concluded that evidence exists for a causal relationship between WR-CTS and occupational risk factors of high task repetition and force. Bernard (1997) agrees based on a meta-analysis undertaken on behalf of NIOSH that a relationship between the occurrence of musculoskeletal disorders and the conduct of work is clear. Strong evidence exists for combinations of physical workplace risk factors. The following occupational risk factors for CTS prevalence have been identified in the literature.

3.1.1.1 Task repetition

Silverstein et al (1986) classified a job as highly repetitive if the cycle time is less than 30 seconds, or if more than 50% of the worktime involves performing the same kind of fundamental cycle. The more repetitive the task, the more rapid and frequent are muscle contractions, which become less efficient. Hence, increased effort requires greater time for physiological recovery.

Based on the above criteria, high repetition is reported to be the single greatest occupational risk factor with a calculated odds-ratio (OR) of 5.5 compared with the general population for carpal tunnel syndrome prevalence in the workplace (Silverstein et al, 1987). Roquelaure et al (1997) found odds-ratios to increase to 8.8 when cycle time for the shortest elementary operation is less than ten seconds.

3.1.1.2 Forceful exertions

As muscle effort increases in response to static and dynamic task loads, circulation to the muscle decreases causing more rapid muscle fatigue (Pheasant, 1994).

Based on CTS prevalence for active workers in high incidence jobs, Silverstein et al (1987) determined high force demands account for an OR of 2.9. Roquelaure et al (1997) found that odds-ratios for forceful exertions increased to 9.0 for external forces greater than 1.0 kg.

There is no agreement to date about what constitutes excessive force. Further, the effect of reducing force alone is difficult to predict (Werner and Armstrong, 1997a)

Jobs that involve both high force and high repetition pose a significantly greater risk than either stressor acting independently, where odds-ratios of more than 15.0 were calculated for the prevalence of work-related CTS (Silverstein et al., 1986).

3.1.1.3 Posture

Awkward postures overload muscles and tendons, load joints in an asymmetrical manner, and impose a static load on the musculature (VanWely, 1970), thereby inhibiting blood and axonal flow.

Certain wrist postures may be particularly stressful due to induced tendon strain. Tension in the finger flexor tendons, such as involved in pinching or grasping tasks, combined with flexion of the wrist causes compression of the underlying median nerve against the taut transverse carpal ligament (Smith et al, 1977).

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 collated, Tanaka et al (1995, 1997) reported that tasks involving bending and twisting of the wrist increase CTS prevalence by 520 to 550 percent.

3.1.1.4 Mechanical pressure

Mechanical pressure is defined as localized contact between body tissue and an object or tool and is often cited as a risk factor for work-related carpal tunnel syndrome. Frequent or continuous use of tools with hard or sharp edges, or short handles causes compression against peripheral nerve fibers, thereby impeding blood circulation and axonal flow (Armstrong, 1986; Armstrong et al, 1987a; Kuorinka and Forcier, 1995).

3.1.1.5 Vibration

Vibrating hand-held tools stimulate muscle contraction and constrict blood vessels, which is described by Armstrong et al (1987b) as toxic vibration reflex. Myelinated nerve fiber and parasympathetic activity is affected, leading to axonal deterioration, which is recognized as depressed peripheral nerve conduction (Murata et al, 1990). The condition is further aggravated as decreased sensory perception causes increased forceful exertions during gripping tasks (Armstrong et al, 1987b).

Tanaka et al (1995, 1997) reported, based on data from the 1988 National Health Interview Survey, that an increased prevalence of CTS of odds ratio 1.8 - 1.9 is associated with the use of vibrating hand tools.

3.1.1.6 Temperature

Exposure to low temperatures produces circulatory, sensory and motor impairments. Decreased motor control may lead to use of compensatory increased forces.

Gloves may be worn in cold environments, which reduce tactile sensitivity. A greater amount of force is exerted to hold or manipulate an object to compensate for perceptual misinterpretations (Putz-Anderson, 1988).

3.1.1.7 Recovery time

Recovery time can exceed actual work time for jobs where physical demands are high. If sufficient recovery time is forfeited, soft tissue injuries may occur (Pheasant, 1994).

Roquelaure et al (1997) found that lack of change in tasks or breaks making up less than fifteen percent of the worktime produced an odds-ratio of 6.0 for carpal tunnel syndrome prevalence among workers.

3.1.1.8 Psychosocial Factors

A study by Kiesler and Finholt (1988) suggests that, if the working environment was better and if the jobs were more satisfying, complaints of musculoskeletal strain would not be as important to the employee. CTS prevalence was described by Nordstrom et al (1997) and Leclerc et al (1998) in terms of dissatisfaction with work and lack of job control, where increased risk expressed as odds-ratios were 2.86 and 2.24, respectively.

As the number of risk factors accumulated by the worker increases, there is a substantial increase in the total odds-ratio for carpal tunnel syndrome prevalence (Roquelaure et al, 1997).

Viikari-Juntura and Silverstein (1999) suggest that while more research is needed, there is sufficient evidence to suggest that reducing the duration, frequency and severity of exposure to forceful repetitive work, extreme wrist postures and vibration will likely to result in a reduction of the incidence and severity of carpal tunnel syndrome in working populations.

3.1.2 Biomechanical Evidence

A significant research effort has been devoted to understanding how carpal tunnel syndrome is affected by the parameters of job demands in hand-intensive work. A summary of the key biomechanical studies is presented, which describe, based on mathematical modeling and laboratory investigations, how imposed loads affect the musculoskeletal structures of the hand and wrist in carpal tunnel syndrome.

3.1.2.1 Static Biomechanical Models of the Wrist

Static biomechanical models have been used to predict the amount of tension in the finger flexor tendons during various work tasks.

When the wrist is straight, the tendons are subjected to a tensile load. However, postural deviation of the wrist causes the finger flexor tendons to be displaced against the walls of the carpal tunnel, creating compressive and frictional forces as the tendons slide across the internal boundaries of the carpal tunnel. In flexion, the finger tendons are pulled over the transverse carpal ligament, compressing the underlying median nerve. In extension the tendons and median nerve are stretched over the carpal bones (Phalen, 1966; Smith et al, 1977; Gelberman et al, 1981) (Figure 18). The angle of the wrist is therefore an important factor in determining the force on the tendon. Exertions of the hand performed with a deviated wrist create a greater force on the tendons than exertions with a straight wrist (Armstrong and Chaffin, 1979b).

Figure 18: Posture induced tendon strain

(from Hitchcock and D'Silva, 1995)
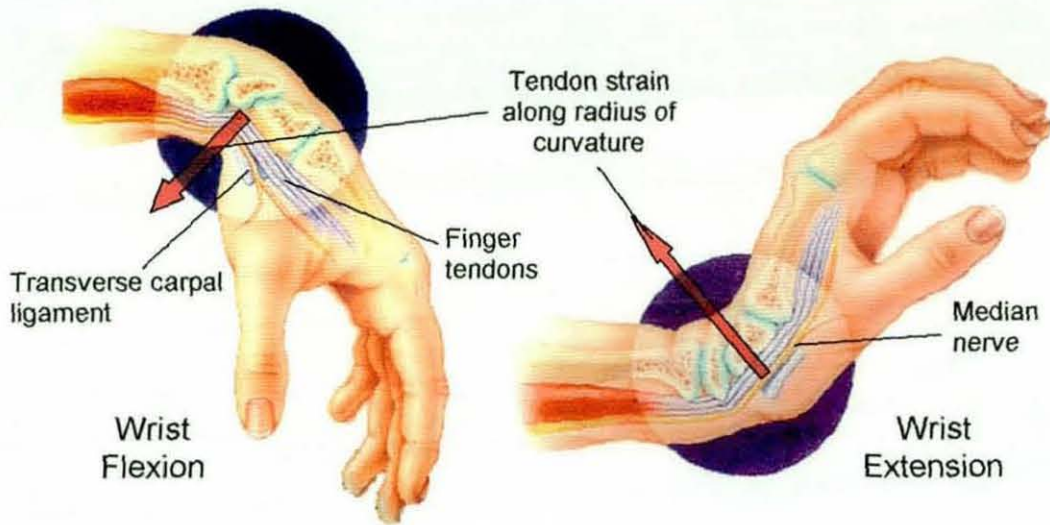
Armstrong and Chaffin (1979b) described that postural deviation of the wrist produces a pulley effect, where tendons exert a contact force against the walls of the carpal tunnel. Tendon forces increase with greater wrist deviations (Goldstein et al, 1987), larger external loads (Keir and Wells, 1992) and specific hand grips (Smith et al, 1977). Internal forces between the tendons and carpal tunnel increase directly with tendon tension and inversely with radius of tendon curvature, causing compression of the synovial membranes that surround the finger tendons. Repeated compression leads to synovial inflammation, causing compression against the median nerve.

Etiological mechanisms of median nerve neuropathy differ between flexed and extended wrist postures. In flexion contact forces between finger flexor tendons and the underlying median nerve are almost twice that measured in extension (Keir and Wells, 1992), resulting in nerve compression against the transverse carpal ligament. In extension, radius of tendon curvature over the carpal bones in the dorsal aspect is greater, over which finger tendons and the median nerve are stretched (Figure 19). Bay et al (1997) demonstrated that tensile stretching of the nerve, which is greater in the distal aspect of the carpal tunnel and in extension, is an important pathomechanical cofactor leading to nerve dysfunction. In addition, extension causes the distal ends of the finger flexor tendons to be drawn into the carpal tunnel, thereby increasing the volume of the contents of the tunnel.

Inflammation of synovial membranes of the tendon structures due to repeated compression further exacerbates nerve stretching in extension.

Figure 19: Tensile strain in median nerve in wrist extension

(from Hitchcock and D'Silva, 1995)

Median nerve is stretched over finger tendons in extension, producing tensile strain

Transverse carpal ligament

Flexor tendons

Median nerve

Repetitive Trauma
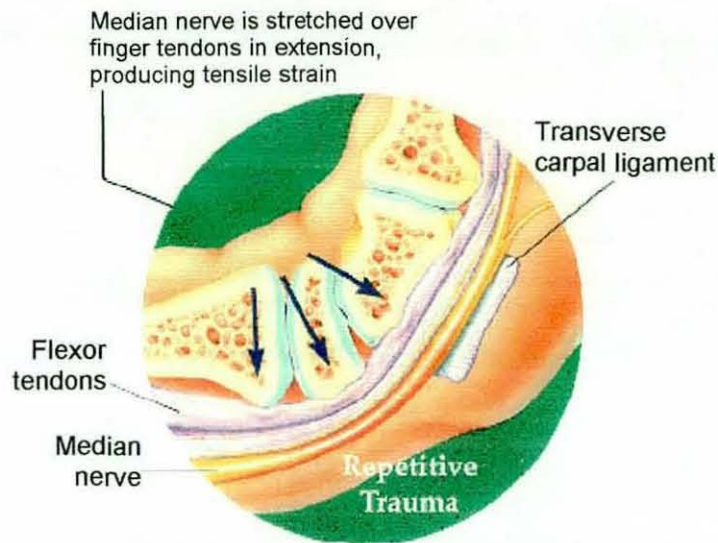
Using biomechanical modeling, Armstrong and Chaffin (1979b) demonstrated that due to decreased radius of tendon curvature, tendon forces against the carpal tunnel would be 14% to 25% greater in flexion and extension, respectively, for smaller female wrists over larger male wrists for similar external loads. This finding may, in part, explain the increased prevalence of carpal tunnel syndrome in female populations.

During pinching and grasping tasks, the finger flexor muscles contract, creating a tension force in the tendon that pulls the tip of the finger in the palmar direction. When a load is applied to the palmar side of the fingers during pressing and grasping actions, mechanical moments are created at the finger and wrist joints. Depending on the grasp type, the tensile force in the muscles and tendons required to oppose these moments is approximately 2.8 to 4.3 times the normal force acting on the fingers (Armstrong, 1976). Due to the effect of longer moment arms, the multiplier is higher when the force is exerted with the fingertips, as when pressing or pinching with the pulps of the distal phalanx. The load is lower when the fingers are wrapped around the object in power hand grip.

3.1.2.2 Dynamic Biomechanical Models of the Wrist

Schoenmarklin and Marras (1990) enhanced Armstrong and Chaffin's static biomechanical model of the wrist to incorporate cyclic loading. Their model proposes that an identifiable sole element of the contact force between the flexor tendons and median nerve is due to cyclic loading.

Dynamic activities create additional tension in the tendons as they pass through the carpal tunnel. When the wrist is accelerated while in a flexed or extended posture, the combined effects of overcoming inertia and the deviated posture create both tensile and normal loads in the tendons that are higher than those required to maintain a static grasp. Furthermore, the load on the tendon increases compression on the median nerve as it passes between the flexor tendons and the flexor retinaculum when the wrist is accelerated during a flexed posture.

3.1.2.3 Wrist Motions in Industry

Marras and Schoenmarklin (1991) conducted a field study to investigate the relationship between dynamic wrist activities and carpal tunnel syndrome incidence. Wrist motions were recorded using an electrogoniometer, which monitored activities in the flexion-extension, radial - ulnar deviation and pronation-supination planes. Mean velocities and accelerations were determined for each participant for each of the three planes of motion. Tasks were then classified based upon low and high levels of wrist activity. Incidence of self-reported CTS amongst participants was then mapped against recorded wrist motions. Results suggest that the magnitude of mean angular acceleration in the flexion-extension plane is a potential predictor of CTS risk. Using logistic regression, the investigators found that self-reported risk of developing CTS increased by 600 percent when wrist acceleration exceeded 824 deg s^{-2}, compared with exposures less than 490 deg s^{-2}.

Further analysis of the data using multiple regression analysis was used to construct a dose-response model to predict incidence of disorders as a function of wrist kinematics (Schoenmarklin and Marras, 1994). Threshold

limits were proposed, where operations involving peak angular wrist accelerations greater than 6,541 deg s^{-2} presented a 98% probability of self-reported CTS incidence among the sample.

3.1.3 Physiological Studies of Intra-Carpal Pressure

Carpal tunnel pressures (CTP) are easily measured using wick catheters that are inserted percutaneously (after the method described by Gelberman et al, 1981). The intra-carpal tunnel pressure has been shown to be significantly higher in CTS patients than in controls, where mean pressures are 26 mmHg and 13 mmHg, respectively (Luchetti et al, 1989, 1990). Highest values are found between 25 and 35 mm distal to the proximal edge of the transverse carpal ligament (Luchetti et al, 1998), which corresponds with the smallest cross sectional area of the carpal tunnel (Robbins, 1963). CTS elevated pressures quickly return to within normal ranges after subcutaneous release of the transverse carpal ligament (Hamanaka et al, 1995).

Wrist posture, tendon forces and external mechanical pressures affect intratunnel pressure, where persistent elevations in CTP may aggravate carpal tunnel syndrome (Keir et al, 1998a). Highest initial pressures as a result of posture alone were found in end-extension (Keir et al, 1997; Luchetti et al, 1998), which continue to rise to an indeterminate maximum if the position is maintained (Thurston and Krause, 1988). Interstitial pressures as high as 94 mmHg and 110 mmHg have been recorded in CTS patients in end-flexion and end-extension, respectively (Gelberman et al, 1981). In a more recent study, Weiss et al. (1995) examined carpal tunnel pressure in four CTS patients and 20 controls. In both patients and controls, CTP followed a parabolic arc as a function of wrist position in the flexion/extension and radial/ulnar directions. In flexion-extension, mean CTP was approximately 100 mm Hg at 60 degrees extension, 5 mm Hg in the neutral position, and 80 mm Hg at 60 degrees flexion. In radial-ulnar deviation, mean CTP was approximately 100 mm Hg at 40 degrees ulnar deviation, 10 mm Hg in the neutral position, and 90 mm Hg at 40 degrees radial deviation. Deviated wrist

postures produce carpal tunnel pressures well above the critical capillary-filling threshold pressure of 32 mmHg among both controls and patients.

Fingertip pressing and pinching tasks produce large intracarpal 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). 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 palmar surface of the hand and wrist have also produced elevated carpal tunnel pressures (Cobb et al, 1995), potentially leading to carpal tunnel syndrome (Madsen and Jensen, 1991).

In a controlled study, Rempel et al (1994) evaluated the effects of manual packaging activities on intratunnel pressures in healthy participants. The study evaluated elements of posture, grasping and mechanical pressure under four test conditions: resting with and without a wrist splint and performing a repetitive task with and without a wrist splint. The repetitive task involved handling 0.45 kg cans 20 times per minute for a period of 5 minutes. Under unsplinted conditions, CTP rose from a median baseline of 8 mm Hg at rest to 18 mm Hg during the task. With the splint, CTP rose from a median baseline of 13 mm Hg at rest to 21 mm Hg during the task. Differences between splinted and unsplinted conditions were not significant. The experimenters concluded that the median nerve was exposed to elevated hydrostatic pressure within the carpal tunnel during repetitive work. The application of a wrist splint did not reduce CTP during work. Carpal tunnel pressure increased at rest with the splint, probably as a result of direct external mechanical pressure on the carpal canal.

3.1.3.1 Intra-Tunnel Pressure Induced Nerve Ischemia

Increased carpal tunnel canal pressure may be a causal factor in the development of a neuropathy of the median nerve at the wrist. Increased

interstitial fluid pressure causes the capillaries to collapse and interfere with the profusion of the median nerve. This condition may cause symptoms of numbness and tingling that are consistent with CTS (Gelberman et al., 1981; Werner et al., 1997).

Experimentally induced and controlled tissue compression at 30 mmHg produces axonal transport impedance with mild neurophysiological changes in median nerve conduction and symptoms of hand paresthesia in asymptomatic subjects (Lundborg et al, 1982; Dahlin et al, 1986). Such changes seem to be due to impairment of the blood flow in the compressed part of the nerve (Rydevik et al, 1981). While short-term (2-4 hours) direct nerve compression produces reversible changes, prolonged compression may prohibit restoration of intra-neural blood flow leading to irreversible nerve damage (Rydevik et al, 1981; Lundborg et al, 1982), exhibited as numbness, paresthesia and pain. Similar pressure levels are commonly observed in patients with carpal tunnel syndrome.

Using magnetic resonance imaging technology, Sugimoto et al (1994) confirmed the above finding in their diagnoses of circulatory disturbance in carpal tunnel syndrome patients. Their conclusions support Sunderland's (1976) hypothesis that vascular mechanism is responsible for CTS. Clinically, the increase of CTS symptoms experienced correlated with the severity of the circulatory disturbance in the nerve.

3.1.4 Summary of the Contribution of Physical Risk Factors in the Aetiology of Carpal Tunnel Syndrome

Evidence from epidemiological, biomechanical and physiological studies reasonably concur with regard to the effects of forceful exertions and awkward postures on carpal tunnel syndrome prevalence (Table 4). Task repetition, while suspected to be the single greatest risk factor based on epidemiological evidence, requires further biomechanical evaluation. Considerable additional research is needed to understand the quantitative relationships between exposure to these factors and the incidence and severity of work-related carpal tunnel syndrome.

Table 4: <u>Summary of evidence-supported physical risk factors</u>

Epidemiological Evidence	Biomechanical / Physiological Evidence
Task repetition	Dynamics of wrist motion (acceleration)
Forceful exertion	Magnitude of grip/pinch/trigger force
	Exertion with finger tip (pinch or pressing action)
Awkward posture	Posture -- wrist flexion or extension
	Posture -- wrist ulnar deviation
	Posture -- work with elevated shoulder
Mechanical pressure	External pressures
Vibration	
Temperature	
Recovery time	
Psychosocial factors	
	Duration of work activity

3.2 Personal Risk Factors

To fully understand the aetiology of carpal tunnel syndrome, it is important to examine personal and health-related factors in addition to occupational risk factors. A worker's ability to accommodate occupational risk factors associated with CTS may be affected by their individual capacity to tolerate such stressors. The intensity, duration, and frequency of the loads imposed on the musculoskeletal system of the wrist, as well as the adequacy of recovery time, are critical components in whether increased tolerance (a training or conditioning effect) occurs, or whether reduced capacity occurs, increasing susceptibility impairment. The capacity to perform work varies among individuals with non-medical personal factors, such as race, gender, age, as well as a variety of confounding medical conditions. The relationship between these factors and the resulting risk of injury to the worker is complex and not fully understood. Loslever and Ranaivosoa (1993) suggest, based on biomechanical and epidemiological evidence, that non-occupational factors may be more important than occupational factors.

3.2.1 Non-Medical Personal Factors

Several non-medical personal factors, including race, gender, age, anthropometric factors and lifestyle conditions have been correlated with increased reporting, which might be indicative of CTS prevalence among the general population.

Based on data derived from the 1988 NIOSH National Health Interview Survey, in which medically confirmed CTS incidence and demographic data for 127 million US workers was correlated, Tanaka et al (1995, 1997) reported that the following non-medical personal risk factors, might increase individual susceptibility to carpal tunnel syndrome. Factors are presented in decreasing order of importance.

3.2.1.1 Race

Whites are reported to be more susceptible to the prevalence of carpal tunnel syndrome by between 420 and 1,670 percent compared with non-white populations (Tanaka et al, 1995; 1997). No other studies of CTS prevalence with respect to race have been documented on which the above findings could be confirmed.

3.2.1.2 Gender

Females are between 220 and 230 percent more at risk of developing CTS compared with males (Tanaka et al, 1995; 1997).

Several studies, including Armstrong and Chaffin (1979a), Miller (1993) and Lam and Thurston (1998) confirm findings of significantly increased incidence among females in the general working population. However, after controlling for work exposure, Silverstein (1985) found no gender difference; a finding confirmed by McDiarmid et al (2000).

Whether the gender difference seen is due to physiological differences or differences in exposure is unclear. The reporting bias may exist because women may be more likely to report pain and seek treatment than men (Armstrong et al., 1993). The fact that more women are employed in hand-

intensive jobs and industries may account for the greater number of reported work-related CTS among women (McDiarmid et al., 2000; US DoL, 2000).

3.2.1.3 Body Mass Index (BMI)

A body mass index (ratio of weight to height squared) of 25 or greater is reported to increase susceptibility to CTS by 200 percent compared with slimmer workers (Tanaka et al, 1995; 1997). Vessey et al (1990), Allen (1995), Stallings et al (1997), Lam and Thurston (1998) and Giersiepen et al (2000) confirm a significant association between obesity and median neuropathy. Sungpet et al (1999) discovered that obesity is a significant risk factor in bi-lateral cases, where the mean BMI for bi-lateral carpal tunnel syndrome was greater than that of patients with unilateral symptoms.

Nathan et al (1994), presented that body mass index is the most important factor for predicting median nerve slowing in industrial workers. However, the methods employed in their studies have been questioned in a number of subsequent publications (Stock, 1991; Werner et al., 1994; Mackinnon and Novak, 1997). Radecki (1995) documented that the likelihood of median nerve slowing as a function of body mass index, in a sample of 946 female participants, was similar between work-related and non work-related cases (Figure 20).

Figure 20: Likelihood of median nerve slowing as a function of BMI
(Radecki, 1995)

53
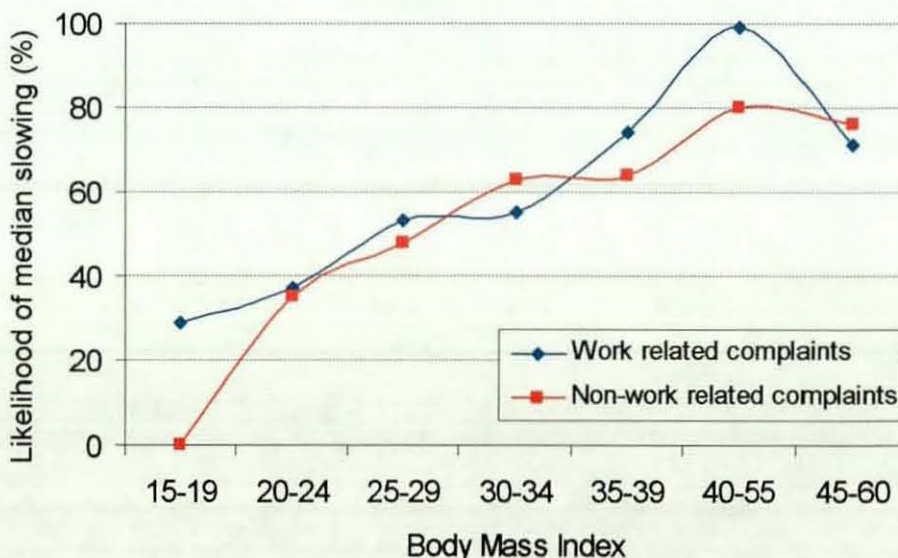
Specifically, Nordstrom et al (1997) defined an increased risk of eight-percent for each one-unit increase in body mass index. This discovery is supported by findings of Werner et al (1994b) who found that individuals whose body mass index exceeded 29 were 2.5 times more likely to be diagnosed with CTS than persons of BMI less than 20. Using multiple linear-regression the investigators highlighted that while BMI was the most influential variable within the population, it still only accounted for 5% of the variance in the model. Obesity seems to play a small but significant role in the occurrence of CTS.

It has been suggested that relationship of CTS with BMI involves increased fatty tissue within the carpal canal or increased hydrostatic pressure throughout the carpal canal in obese persons compared with slender persons (Werner et al., 1994b).

3.2.1.4 Cigarette Smoking

History of cigarette smoking presents an increased risk of developing CTS of 1.6 (odds-ratio) compared with non-smokers (Tanaka et al, 1995; 1997). Further, Vessey et al (1990) found that physician referral rates for CTS symptomatic experience almost tripled in smokers. Nathan et al. (1996) stated that greater use of tobacco combined with greater consumption of caffeinated beverages and alcohol abuse was associated with electrophysiologically confirmed CTS. However, the effects explained only a small portion of the total risk.

3.2.1.5 Age (Aging)

Risk of CTS prevalence increases by three percent per year. Categorically, active workers over 40 years old are 20 percent more at risk than are younger workers (Tanaka et al, 1995; 1997).

Cohort studies performed by Vessey et al (1990), Ferry et al (1998b), and Lam and Thurston (1998) presented similar findings of increased susceptibility to carpal tunnel syndrome among aged workers. Radecki (1995) discovered that the likelihood of median nerve slowing as a function of age

was similar between work-related and non work-related cases (Figure 21), suggesting that median slowing is part of the natural aging process.

Figure 21: Likelihood of median nerve slowing as a function of age
(Radecki, 1995)
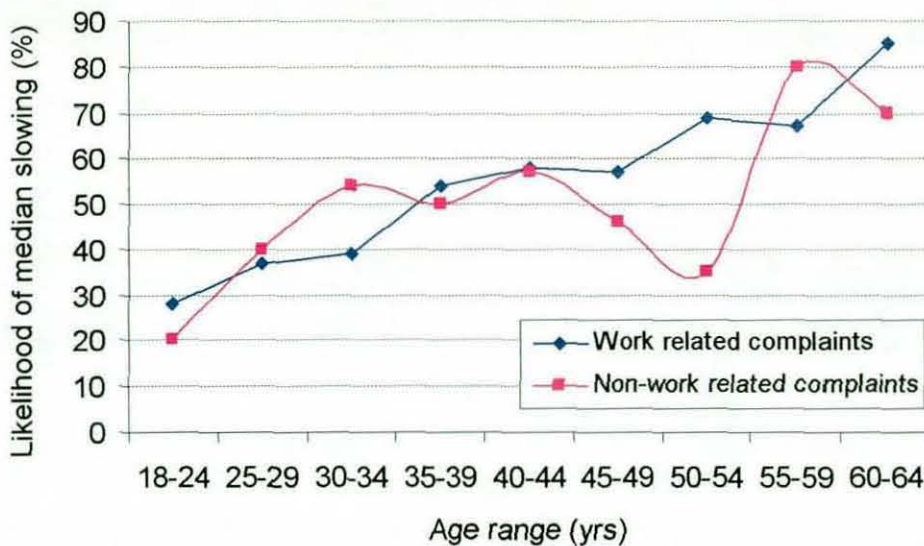
Though data presented suggest an association between age and CTS risk, age may be incorrectly attributed as the sole cause in some findings (Schottland et al., 1991). Advancing age is usually highly correlated with increasing number of years working, which may be expressed as duration of exposure to physical stressors. It would seem reasonable, therefore, to statistically separate these potential confounders.

Investigations into the effect of age (aging) on aetiology of work-related carpal tunnel syndrome may be further confounded by a potential "survivor bias". If workers with health problems leave the workforce, or change to jobs with less exposure, the remaining population would include only those workers whose health has not been adversely affected by their jobs. The effect of which may be an underestimate of the true risk of developing work-related carpal tunnel syndrome in older workers.

3.2.2 Medical Conditions and Diseases

Medical conditions or diseases that contribute to the development of carpal tunnel syndrome are common (Robbins, 1963; Chabon, 1985; Pascual et al, 1991; Nathan et al, 1994; Osorio et al, 1994; Chammas et al, 1995; O'Riordan et al, 1995; Pfalzer and McPhee, 1995; Nordstrom et al, 1997 and Solomon et al, 1999) (Figure 22).

Figure 22: Confounding effects of medical conditions

(from Hitchcock and D'Silva, 1995)
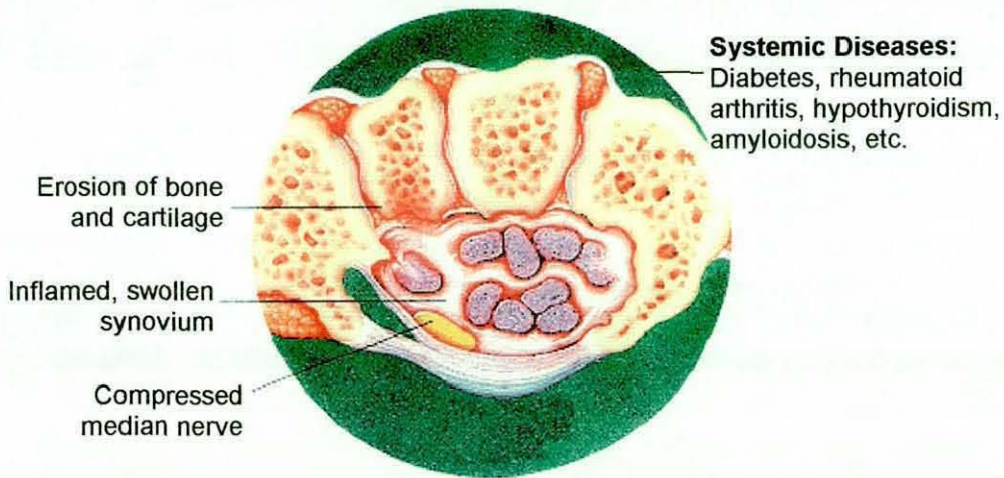
Atcheson et al (1998) diagnosed one-third of patients reporting work-related carpal tunnel syndrome with confounding diseases and proposed the need to explore such issues with patients beyond historical review.

3.2.2.1 Anatomical Variations

Compromise of the area of the carpal tunnel due to irregularities of the carpal bones, thickening of the transverse carpal ligament, hypertrophic synovium, acromegaly, myxedema or congenital abnormalities lead to increased intra-tunnel pressures.

3.2.2.2 Increased Volume of Canal Contents

Increased volume of the contents of the canal increases intra-tunnel pressures, thereby producing circulatory consequences. Traumatic causes include Colles fracture, Volkman ischemic contracture, distal radial and ulnar fracture callus, post-traumatic osteophytes, carpal bone dislocation, pseudoarthrosis of scaphoid and degenerative joint disease. Non-traumatic causes include: neoplasms, benign cysts and malignant tumor of the bone, neuroma, lipoma and ganglions.

3.2.2.3 Abnormal Vasculature

Vascular variations including persistent median artery, permanent shunt for renal dialysis, hematoma, Raynaud's phenomenon, and other circulatory disturbances contribute to ischemia.

3.2.2.4 Abnormal Musculature

Anatomical variations in the muscle bellies of the flexor digitorum sublimis or lumbricals have been associated with increased susceptibility to the syndrome due to contraction against the nerve.

3.2.2.5 Anatomic Variations in the Median Nerve

Variations in the median nerve may reduce vasculature due to increased distances between the nerve and supporting vascular vessels. Examples include high nerve division in the forearm, variations in thenar innervation, and accessory branch proximal to the carpal tunnel.

3.2.2.6 Neuropathic Conditions

Increased prevalence of CTS has been associated with diabetes mellitus, alcoholism, proximal lesion of median nerve (double crush syndrome) and polyneuritis.

3.2.2.7 Inflammatory / Autoimmune Disorders

Rheumatoid arthritis, polymyalgia, gout, amyloidosis, calcific tendonitis, tenosynovitis, suppurative tendonitis, and Lupus erythematosis have been associated with increased incidence of CTS due to inflammatory restriction of the cross-sectional area of the tunnel.

3.2.2.8 Hormonal / Metabolic Disorders

Increased incidence of CTS has been associated with eclampsia, myxedema, renal failure, obesity, and hypo and hyper-thyroidism, due to altered hormonal balances causing connective tissue changes similar to an inflammatory response.

3.2.2.9 Systemic Diseases

Systemic diseases associated with increased CTS include hypertension, kidney disorders, acromegaly and cystic fibrosis.

3.2.3 Hereditary traits

Familial carpal tunnel syndrome (FCTS) is a rare genetically distinct disorder, with differing demographic features from work-related CTS (Gossett and Chance, 1998). FCTS is suspected to be due to manifestation of a systemic disease (Stoll and Maitrot, 1998), in which earlier onset and increased bilateral involvement is noted in later generations (Gossett and Chance, 1998).

A study undertaken by Radecki (1994) to determine the prevalence and significance of familial CTS found that 75 percent of 253 females and 40 percent of 168 males with clinically confirmed carpal tunnel syndrome had at least one relative with a prior history of the syndrome. Further investigation of CTS severity using electrodiagnostic techniques determined that 39.3% of patients with median nerve slowing had a positive family history.

3.2.4 Reproductive Factors

Pregnant, menopausal and post hysterectomy patients are more susceptible to carpal tunnel syndrome. It is thought that increased incidence among these patients is due to an alteration of fluid balance, leading to an increase in the volume of the contents of the carpal tunnel and thereby causing median nerve ischemia (Pascual et al, 1991).

Studies of clinical and electrophysiological features in cases of CTS associated with pregnancy discovered a higher incidence of persistent, painful symptoms, than in idiopathic CTS (Atisook et al, 1995; Seror, 1998). Although onset of pregnancy-related CTS may occur at any time during the pregnancy, diagnosis is made most often during the third trimester, when patients are most edematous. Most cases (96%) resolve after pregnancy reaches full term (Stolp-Smith et al, 1998).

History of gynecological surgery, specifically hysterectomy and oophorectomy (ovarian surgery), and hormonal changes of menopause are strongly associated with the onset of carpal tunnel syndrome (Cannon et al, 1981; Pascual et al, 1991). Prevalence of CTS may also increase due to prolonged use of oral contraceptives (Vessey et al, 1990; Ferry et al, 2000).

3.3 Pathophysiology of Work-Related Carpal Tunnel Syndrome

Extending from the overview of risk factors associated with carpal tunnel syndrome prevalence, offered in figure 17, the following speculative model was developed, based on evidence in the literature to document the progressive pathophysiological process (Figure 23). Corresponding symptomatic presentation, from mild sensory impairment through chronic motor deficit, is described. Differentiation between a physiologic response and pathologic consequence is offered along with classification for clinically evident carpal tunnel syndrome.

Figure 23: Aetiology of carpal tunnel syndrome - a speculative model based upon a review of the literature
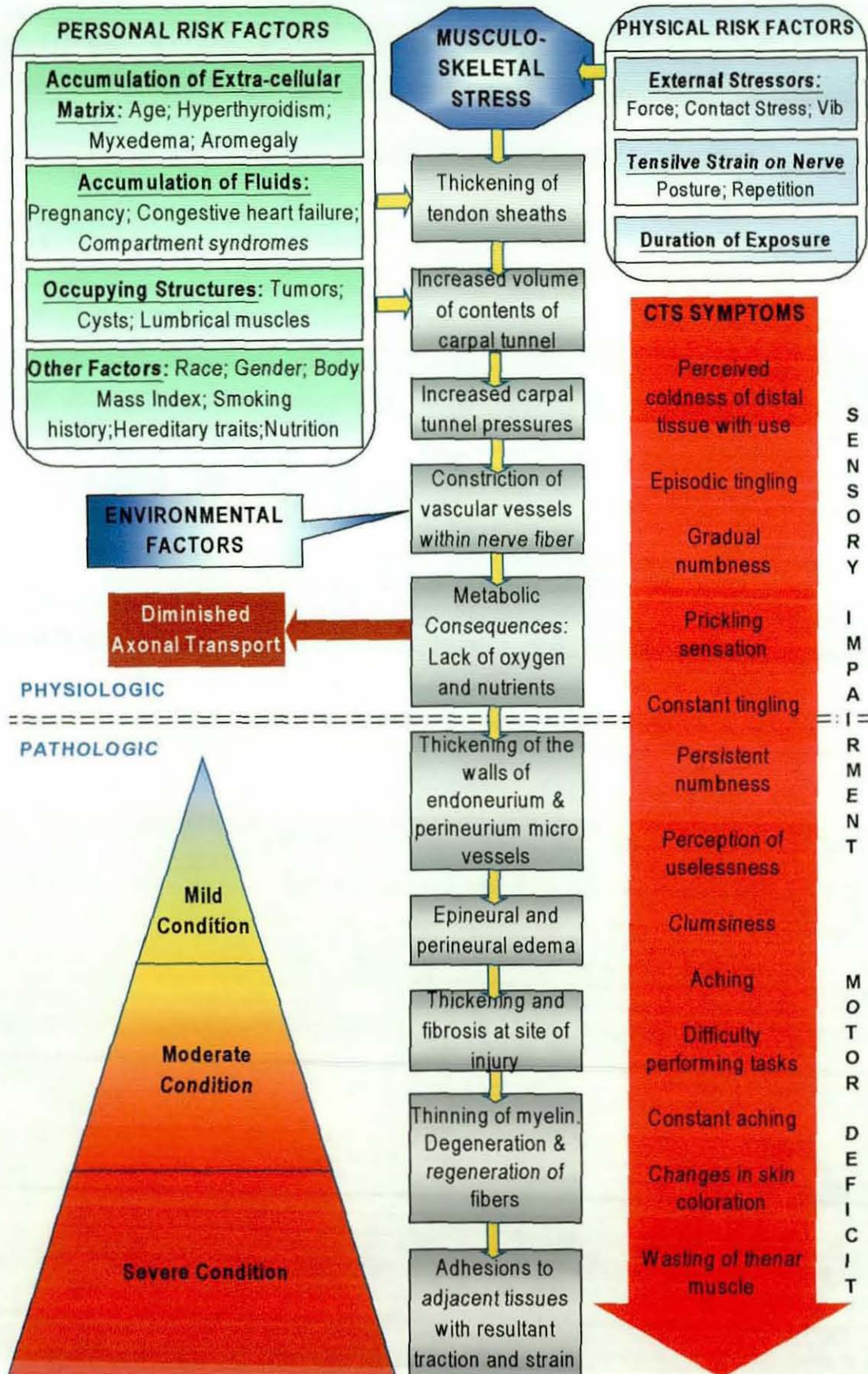
Evidence in the literature document associations between personal risk factors and peripheral neurological function. These include both mutable (e.g. smoking, nutrition) and immutable (e.g. age, race, gender) factors. Individual factors can cause a thickening of the tendon sheaths, or increase the volume of the contents of the carpal tunnel, as illustrated in the flowchart, thereby affecting baseline neurological function and resting symptomatic experience.

Meta-analyses (Stock, 1991; Bernard, 1997; NAS 2001) have concluded that there is reasonable evidence from epidemiological and biomechanical studies that certain work factors or combinations of factors can cause or significantly contribute to the development of carpal tunnel syndrome. Repetitive activity, forceful exertions and non-neutral wrist postures may lead to increased compressive, frictional and tensile forces on the flexor tendons and their sheaths. The increased forces can cause edema or degenerative changes within the tendon sheaths, the duration before onset of which may be a function of task demands and co-existing factors. If sufficient opportunity for physiological recovery is provided, equilibrium is soon restored.

Continued employment of the overused extremity before it has fully recovered can produce a progressive pathophysiological response, as illustrated. Long-standing edema or degenerative changes can lead to a thickening of the flexor tendon sheaths, which is the most commonly reported gross anatomical change in CTS patients (Tanzer, 1959; Phalen and Kendrick, 1957; Phalen, 1966). Histopathological studies have almost uniformly demonstrated a lack of inflammation (Fuchs et al., 1991; Neal et al., 1987). Instead, edema, collagen bundle thickening, degradation and fibrous hyperplasia of the synovial membrane, or vascular sclerosis are often reported (Armstrong et al, 1984; Fuchs et al., 1991; Neal et al., 1987; Kerwin et al, 1996). This may be further aggravated by responses to intrinsic personal risk factors, such as pregnancy, systemic diseases, etc.

The carpal tunnel is a confined space. Normally there is little free space. Any physiologic or pathologic process that reduces its capacity or increases its volume can increase interstitial pressures (Cobb et al, 1992).

Since the median nerve is fragile compared to surrounding structures, it compresses as the available volume of the carpal tunnel is compromised.

As illustrated in the speculative flowchart, the symptoms of CTS can be explained on the basis of ischemia caused by increased intracarpal pressure (Lundborg and Dahlin, 1989; Szabo and Gelberman, 1987) and further compounded by adverse environmental factors. Sensory type A fibers are large myelinated fibers that relay impulses associated with pressure, touch, temperature, muscle tension and joint position. These large nerve fascicles are sensitive to ischemia. During periods of ischemia, there is an observed reduction of sensory nerve function (Stohr, 1980).

Effective neural communication is highly dependent on an adequate oxygen supply (Lundborg, 1970). When pressures on the microvascular vessels within the median nerve rise above a critical threshold, venous obstruction causes capillary blood flow to be reduced below the level required for nerve viability (Szabo, 1998). Even small elevations in pressure are associated with reduced intrafascicular blood flow (Gelberman et al, 1981; Lundborg, 1982). The resulting metabolic consequences of lack of nutrients and oxygen cause axon degeneration (Pease et al, 1990; Seror, 1996), which produces characteristic nerve conduction disturbances and symptoms associated with neurological impairment.

Without intervention, a pathologic consequence may ensue in the nerve fibers. The walls of the endoneurium and perineurium can become thickened. There may also be an increase in edema in the nerve fibers. In the most severe cases, adhesions between the nerve fibers and adjacent tissues are sometimes evident, which can further compound the strain on the nerve.

As the long-term degenerative nature of carpal tunnel syndrome progresses from mild to severe, motor deficits are realized. This may be reported subjectively as constant aching and difficulty performing tasks. Clinically, motor deficit can lead to eventual wasting of the thenar muscle.

3.4 Current Voids in the Research Knowledge

Although numerous studies have suggested that carpal tunnel syndrome develops due to prolonged exposure to force, frequency, posture and vibration stressors, no clear "dose-response" relationship has yet been determined between the amount or intensity of work and the incidence or severity of the syndrome (Katz, 1994; Hadler, 1997). Establishment of the work-relatedness of these disorders requires both the quantification of exposures involved in work and a reliable objective determination of health outcomes.

The evidence in the literature presents agreement between epidemiological and biomechanical findings for occupational risk factors of forceful exertion and awkward posture. Task repetition may be the single greatest risk factor associated with the prevalence of carpal tunnel syndrome among working populations, however, biomechanical studies to date have failed to address this important issue independent of other factors. This research study considers the effect of repetitive wrist motion on median nerve function exclusive of other physical factors that might contribute to tendon forces.

CHAPTER 4: METHODS AND PROCEDURES

This chapter will describe the methodological elements of this study, including research design, sample, recruitment, screening and selection criteria, experiment conditions, variables, measurement, site, data collection protocol and data management.

4.1 Research Design

A repeated-measures laboratory study was designed in which subjects served as their own controls. Twenty-seven clinically confirmed asymptomatic female participants were asked to perform repetitive wrist motion in the flexion-extension plane, the intensity and duration of which was randomized across four prescribed conditions.

Wrist motion was recorded using a state-of-the-art 3D electromagnetic tracking system (HumanTRAC). Sensory median nerve response to imposed physical stressors was monitored antidromically and recorded using a clinical electroneurometer every ten minutes throughout the simulated work activities. Near-nerve skin temperature was recorded at three sites along the distal sensory branch of the median nerve every twenty minutes.

4.2 Sample

Given a minimum acceptable power of 0.8, a significance level of $\alpha=0.05$ and a ten percent expected change in sensory median nerve function (effect size), power analysis determined that a minimum sample size 29 subjects was necessary to detect a statistically significant dose-response effect (Table 5). Effect sizes were estimated based on pilot study data since pertinent data were not available in the literature. A subject dropout rate of twenty percent was estimated considering task repetition and monotony. Thus, a total of 35 qualifying participants were sought for the study.

Table 5: <u>Power analysis for statistical design</u>

Number of Subjects	Significance level $p = 0.05$	Beta (Type II error)	F (power)
16	0.05	0.480	0.520
23	0.05	0.304	0.696
29	**0.05**	**0.197**	**0.803**
38	0.05	0.096	0.904
50	0.05	0.033	0.967

To achieve a significance level of $\alpha=0.01$, sample size requirements would increase to 54, all other factors remaining constant. While a higher significance level was desirable, it was not attainable because of subject recruitment difficulties. One possible explanation for this may be a positive local economy. A higher level of compensation might have attracted a larger number of responses to advertising, thereby increasing the number of qualifying candidates.

Power analysis was revisited after completing data collection on 27 participants, which revealed a higher than expected effect size across subjects, thereby satisfying minimum standards for acceptable power.

4.2.1 Inclusion Criteria

Only asymptomatic females between the ages of 18 and 45 were included in the study.

1. The sample was limited to females, since Tanaka (1995, 1997) suggested that females are more likely to experience symptoms associated with nerve disorders, than are males.

2. Age range was limited to 18 to 45 years. This age range is representative of an adult working population, while minimizing menopausal confounders in the all-female sample.

3. Medical evaluations were performed to ensure that participants were clear of symptomatic and clinical evidence of upper extremity musculoskeletal disorders.

4. Only the dominant hand was studied.

4.2.2 Exclusion Criteria

Candidates who presented clinical evidence of musculoskeletal disorders of the upper extremity, or heightened susceptibility thereto, were precluded from participating in the study.

1. Persons who had been previously diagnosed with certain precipitating medical disorders, including diabetes, rheumatoid arthritis, gout, cystic fibrosis, thyroid or kidney disorders, hypertension, etc., or presented *hematological evidence of such, were excluded from the study.*

2. Candidates with a musculoskeletal disorder of the dominant upper extremity, either acute or cumulative, were excluded.

3. Candidates who exhibited hormonal imbalance because of pregnancy, menopause, hysterectomy or use of the birth control pill were precluded.

While it is suspected that carpal tunnel syndrome may be more prevalent among Caucasian populations, the Investigative Review Board deemed it unacceptable to preclude any participants based on race.

4.3 Recruitment, Screening and Selection Criteria

4.3.1 Subject Recruitment

Subjects were recruited from the Tampa Bay area by means of poster advertisement (Appendix 2). Letter-size color posters were placed around the James A. Haley Veterans' Hospital in compliance with protocol filed with the University of South Florida's Investigative Review Board (IRB) (Attachments

3A-3D). The research protocol was also reviewed and approved by the Ethics Committee at Loughborough University (see Attachment 3E).

After two weeks the recruitment strategy was reviewed. It was discovered that the posters were attracting considerable attention from interested candidates, however pre-screening precluded ninety percent of all callers primarily due to use of oral contraceptives. The recruitment poster was revised to more clearly state desired participant characteristics, so improving caller qualification rate. In addition, sources were broadened to include faculty, staff and students of the University of South Florida. The USF IRB protocol was updated to reflect this revision, which was subsequently approved. With the above revisions, subject recruitment goals were achieved.

4.3.2 Pre-Screening of Potential Candidates

A brief description of the study was read to all respondees from a pre-formatted transcription (Appendix 3A), after which they were asked if they wanted to continue with the application. Interested callers were then asked a series of seven pre-qualifying questions, pertaining to availability, gender, age, symptomatic experience or diagnosis of upper extremity musculoskeletal disorder or injury, reproductive order, and evidence of confounding systemic diseases (Appendix 3B). This step was necessary to minimize the number of unsuitable candidates who took part in the costly medical evaluation. Candidates who provided desirable answers to all of the pre-qualification questions were asked to provide contact information (Appendix 3C) for medical evaluation scheduling purposes.

4.3.3 Medical Evaluation

Following subject recruitment an appointment was made at the convenience of each candidate to meet with Dr. Robert Belsole and John Lloyd at the Harborside Medical Clinics of Tampa General Hospital in Tampa,

Florida. This meeting served as a medical evaluation for screening potential candidates (Figure 24).

Figure 24: Medical evaluation protocol

Informed Consent

+

General Questionnaire:
age; gender; race; occupational history;
participation in hand intensive activities

+

Detailed Health Questionnaire:
historical considerations and
confounding medical conditions

+

Baseline Subject Comfort Survey:
symptomatic indication chart and
linear comfort rating scale

+

Anthropometry
Subject height and weight
Hand anthropmetry
Hand strength - pinch and power grip
Hand volume
Skin fat

+

Clinical Evaluation and Patient History
Standardized clinical tests for carpal tunnel
syndrome performed by Dr. Robert Belsole

+

X-Rays:
of the carpal tunnel to identify past or present
skeletal abnormalities

+

Blood Sample:
CBC & Sed. Rate as means of determining
presence of confounding systemic diseases

The goal of the medical evaluation was to recruit 35 healthy participants from the candidate pool. Healthy is defined as nonexistence of clinical indicators of upper extremity musculoskeletal disorders or heightened susceptibility thereto.

The medical evaluation lasted approximately two hours total per subject. It was possible to assess up to five candidates per day, however a large number of scheduled candidates repeatedly failed to attend the evaluations. Hence, medical evaluations were scheduled weekly for a period of four months to attain the desired sample. Forty-one evaluations were completed, from which 34 clinically asymptomatic potential participants were identified. The candidates were compensated $20.00 (twenty dollars US) for their time irrespective of the findings.

Upon arrival at the medical clinics, the subjects were presented with an Informed Consent document (Attachment 3B), which they were asked to carefully read and retain for their records. Questions pertaining to the study were encouraged and answered to the satisfaction of the candidates, with the exception that participant knowledge of the desired outcome might influence validity of the findings. Candidates were then asked to sign the informed consent before proceeding with the medical evaluation.

Following expressed written consent, the participants were asked to complete a General Questionnaire (Appendix 1A), a detailed Health Questionnaire (Appendix 1B) and a Subject Comfort Survey (Appendix 1C). Information derived from these questionnaires was used both to preclude unsuitable candidates from the study in cases were a heightened susceptibility to upper extremity musculoskeletal disorders was evident and as a general health record for included participants.

A series of anthropometric measures were then recorded (Appendix 1D) according to U.S. army guidelines (Clauser et al, 1988) (Appendix 1E). Stature and weight were measured using a Physician's dual scale (Figure 25), from which Body Mass Index (BMI) was determined. Ten standard hand anthropometry measures were recorded using precision calipers (Figure 26). Hand volume was measured using a hand volumeter, where hand volume was equal to the total volume of water displaced (Figure 27). Skin fat across a skin fold midway along the inside of the forearm was measured using skin fat calipers as a record of local soft tissue density. Finally, pinch and power grip strengths were determined using dynamometers to evaluate muscle function and to investigate for evidence of atrophy (Figure 28).

Figure 25: <u>Stature measurement</u>   Figure 26: <u>Hand anthropometry</u>

Figure 27: <u>Hand volume</u>   Figure 28: <u>Power grip strength</u>

Robert Belsole, M.D., a distinguished hand surgeon and carpal tunnel syndrome specialist performed a comprehensive medical evaluation of each candidate to ensure their suitability for inclusion in the study.

The physical examination comprised a review of the candidates historical file, structured interview and various clinical tests for CTS, including range-of-motion testing of the neck, shoulder, elbow, forearm and wrist, pronator compression test (Figure 29), forearm compression test, passive Phalen's maneuver (Figure 30), reverse Phalen's maneuver, Allen's test, Adson's test, DTR, CMC and trigger digit test. These tests are described in detail in the literature review section of this report. Any indication of pain or discomfort by the candidate during the execution of these tests necessitated

their preclusion from the study due to the possibility of an existing upper extremity musculoskeletal disorder.

Figure 29: <u>Pronator compression test</u>   Figure 30: <u>Passive Phalen's test</u>

X-rays of the dominant wrist, including anterior-posterior view (Figure 31), lateral view (Figure 32) and carpal tunnel view (Figure 33) were ordered to investigate the presence of skeletal abnormalities or past or present injury.

Figure 31: <u>X-ray of the wrist (anterior-posterior view)</u>

Figure 32: <u>X-ray of the wrist (lateral view)</u>

Figure 33: <u>X-ray through the carpal tunnel</u>

CBC and sed-rate testing of a blood sample from each of the subjects was performed to ensure that systemic diseases or other identifiable medical conditions did not confound the risk of developing CTS. Subjects were excluded from participating in the study if positive findings were reported for any of the above-described tests.

Results of the medical evaluations were not available on the day of testing, therefore the candidates were later advised of their eligibility for the study by telephone. Before leaving the examination, the candidates were given a Project Description and Appointment sheet on which they could record their appointment details when called.

4.3.4 Selection

The first 27 voluntary subjects who passed the medical evaluation were invited to participate in the study.

4.4 Study Population Characteristics

4.4.1 Subject Participation and Attrition

Recruitment efforts identified 34 healthy candidates from 195 respondees, of whom 27 participated in the study. Three participants exercised their right under the voluntary stopping rule to leave the study.

Reasons presented included discomfort in the dominant upper extremity and discomfort associated with prolonged sitting (Appendix 4, Table 1).

4.4.2 Participant Demographics

The average age of the all-female study population was 34.7 years (range 19–45 years). Participant racial makeup was 26 white, one African-American. The right hand was dominant in 26 of the 27 participants. None of the subjects were taking medications at the time of their selection and participation, including oral contraceptives. There were 20 non-smokers, 4 past smokers and 3 present smokers (Appendix 4, Table 2).

Candidates were screened for engagement in hand-intensive occupational or leisure activities. Of the 27 females who participated in the study, there were eight medical personnel (including 4 nurses), eight office staff (including 4 administrative assistants and 3 sales persons), five students, two food service industry employees, and three unemployed persons.

4.4.3 Subject Anthropometry

The average body-mass-index (BMI) of the experimental sample was 26.6 (range 21.4 – 39.6). Dominant hand mass averaged 342.7grams (range 278.4 – 423.4g), while dominant hand volume had a mean of 295.4 ml. (range 240 – 365 ml.) (Appendix 4, Tables 3 and 4).

4.4.4 Medical Screening

One participant reported prior diagnosis of carpal tunnel syndrome, including symptoms associated with activities of daily living (ADL). Based on self-reporting it is believed that the individual's condition was attributable to a pregnancy ten years prior, where symptoms passed after her pregnancy

reached normal term. Evaluation by the clinician revealed no present symptoms or aggravating conditions associated with the syndrome.

Use of oral contraception was screened, due to possible physiological effects similar to pregnancy, using self-reporting techniques. One candidate reported prior use of such prescription medication, but had not used the medication for more than one year.

None of the subjects reported prior diagnosis of any known confounding systemic diseases, such as diabetes mellitus, gout, rheumatoid arthritis, fibromyalgia, etc. (Appendix 4, Table 5).

Ten subjects reported familial incidence of diabetes, two thyroid disease, and one rheumatoid arthritis. Childhood medical history was learned through questionnaires, the results of which did not present any reason for exclusion.

Radiographic views of the carpal tunnel and wrist were normal in all participants. Ulnar prominence with respect to the radius was recorded (Appendix 4, Table 6).

The number of days between the start of each participant's last menstrual cycle and task participation was estimated based on data solicited using the Health Questionnaire (Appendix 1B) (Appendix 4, Table 7).

Range of motion of the neck and upper extremities was normal in all subjects (Appendix 4, Table 8).

Clinical evaluation by the physician based on thirteen provocative tests and observations for carpal tunnel syndrome revealed no present symptoms in any of the study population. Skin changes were observed in one participant, however it was determined that this was due to an unrelated medical condition (Appendix 4, Table 9).

Furthermore, during the data collection phase of this study, baseline measures of sensory median nerve function were acquired at the start of each day. Reference to normal values indicated that all subjects were asymptomatic prior to exposure to prescribed wrist activities. Length of the stimulated nerve fibers was measured for use in nerve conduction velocity calculations (Appendix 4, Table 10).

Blood work results from qualifying subjects did not present any evidence of systemic diseases (Appendix 4, Table 11).

4.5 Standardized Task Conditions

The objective was to produce wrist activity levels indicative of low, medium and high-risk repetitive tasks. Low risk is defined as those tasks producing mean angular accelerations less than 490 deg s^{-2}; medium risk is defined between 490 deg s^{-2} and 820 deg s^{-2}; and high risk defined as those tasks producing mean wrist accelerations greater than 820 deg s^{-2} (after Marras and Schoenmarklin, 1991a, 1991b). For this study, mean angular wrist accelerations in the order of 200 deg s^{-2}, 600 deg s^{-2} and 1000 deg s^{-2} were selected.

4.5.1 Experiment Conditions

A matrix was designed to evaluate the effect of combinations of wrist activity and duration of exposure. Three levels of duration of exposure (low = 2 hours, moderate = 4 hours, and high = 6 hours) and four levels of wrist activity, expressed as mean angular accelerations of the wrist (static = 0 deg s^{-2}; low = 200 deg s^{-2}; medium = 600 deg s^{-2}; and high = 1000 deg s^{-2}), were prescribed (Table 6). Participants were asked to complete all conditions, where subjects served as their own controls.

Table 6: Experiment design matrix

		Duration of Exposure		
		Low (2hrs)	Medium (4hrs)	High (6hrs)
Wrist Acceleration	Static (0 deg s^{-2})	X	X	X
	Low (200 deg s^{-2})	X		
	Medium (600 deg s^{-2})	X	X	
	High (1000 deg s^{-2})	X	X	X

Task assignments were randomized both between and within workdays using random number tables (Appendix 5A). Fourteen of the 27 participants started day one at the low / medium activity level; the remainder were assigned the high activity condition (100 deg s^{-2} for 6 hours) on day one. Since both the low (200 deg s^{-2} for 2 hours) and medium (600 deg s^{-2} for 4 hours) tasks could be completed within the same workday, intra-day task assignment for these conditions was also randomized, such that 15 participants commenced at the low activity level, and 11 subjects started at the medium activity level. Thirteen participants also completed a static condition (0 deg s^{-2} for 6 hours). This experiment design provided 130 sessions of data (Table 7).

Table 7: <u>Group samples</u>

Condition	Session 1		Session 2		Session 3
0	N=13	B	N=13	L	N=12
Low-AM	N=15	R		U	
Low-PM		E		N	N=11
Med-AM	N=11	A	N=11	C	
Med-PM		K	N=15	H	N=15
High	N=26		N=24		N=24
Total	N=65		N=63		N=62

4.5.2 Development of Experiment Conditions

The purpose of this computation was to map wrist activity, expressed as a function of mean angular acceleration, onto corresponding task frequencies for repetitive flexion-extension activities.

Initial investigation of corresponding task frequencies involved repetitive wrist flexion-extension activities, producing an arc of 120 degrees about neutral, were performed by the investigator between task frequencies of 20 and 200 repetitions per minute (RPM). Wrist motion data at each of these frequencies were recorded using a Greenleaf Wrist Monitor.

The Greenleaf wrist monitor is a commercially available objective measurement tool that is comprised of two uni-axial electrogoniometers fitted into a nylon glove that is worn by a subject (Figure 34). Data from the electrogoniometers is streamed into a Windows 95™ computer software program at recording frequencies up to 100 Hz. For the purpose of this evaluation, the maximum data recording frequency was chosen to enhance confidence in the findings.

Figure 34: Greenleaf wrist monitor

Visual inspection of the angular displacement versus time output revealed that the wrist motion activities produced sinusoidal waveforms (Figure 35).

Figure 35: Angular displacement of wrist motion

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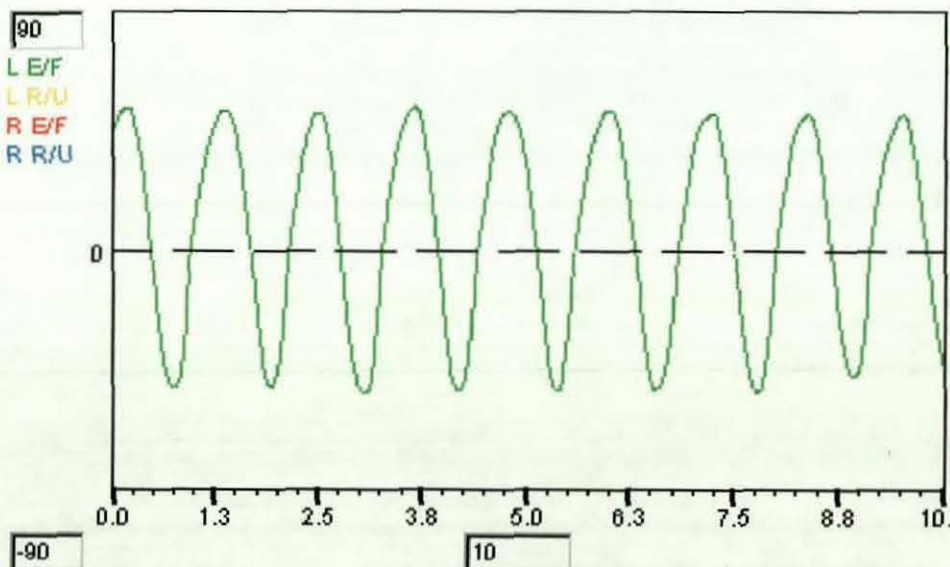
Analysis of the wrist motion data proved difficult due to irregular data characteristics of the hardware filters in the Greenleaf Wrist Monitor. Various numerical differentiation techniques were employed for the purpose of determining mean and peak angular wrist accelerations at each of the recorded task frequencies. Convolution intervals were initially favored due to the robustness of the formulae for smoothing data irregularities. However, trial revealed that this technique actually amplified the irregularities, thus further distorting the true result.

Step-size sampling differentiation methods proved a more effective technique for mathematically managing the data irregularities. Step sizes between two and ten were evaluated. Results showed that mean wrist velocity and wrist accelerations were more reliable with step sizes of at least ten. Larger step sizes were warranted, however, after twice differentiating the angular displacement data set, wrist accelerations were being computed over a 100-point spread. Given a maximum sampling rate of 100Hz, this technique began to smooth the waveform rather than only the data irregularities, especially for task cycle times less than or equal to one second.

Based on the earlier observation of similarities between angular wrist displacement and true sinusoidal waveforms of the same amplitude and cycle time, an assumption was made that mean angular velocities and accelerations computed for sinusoidal waveforms would approximate those for natural wrist motion data. The following graph illustrates the similarity between a wrist motion waveform produced for a task of frequency 30 RPM and a sinusoidal waveform of the same amplitude and cycle time.

Slight differences between the two waveforms are due to measurable irregularities in natural human motion. However, when averaged over a longer duration than one cycle, characteristics of natural human motion should approach those of a sinusoidal waveform. Therefore, a good correlation should exist between the mean angular velocities and accelerations of both waveforms.

Figure 36: Comparison of natural wrist motion to a sinusoidal waveform
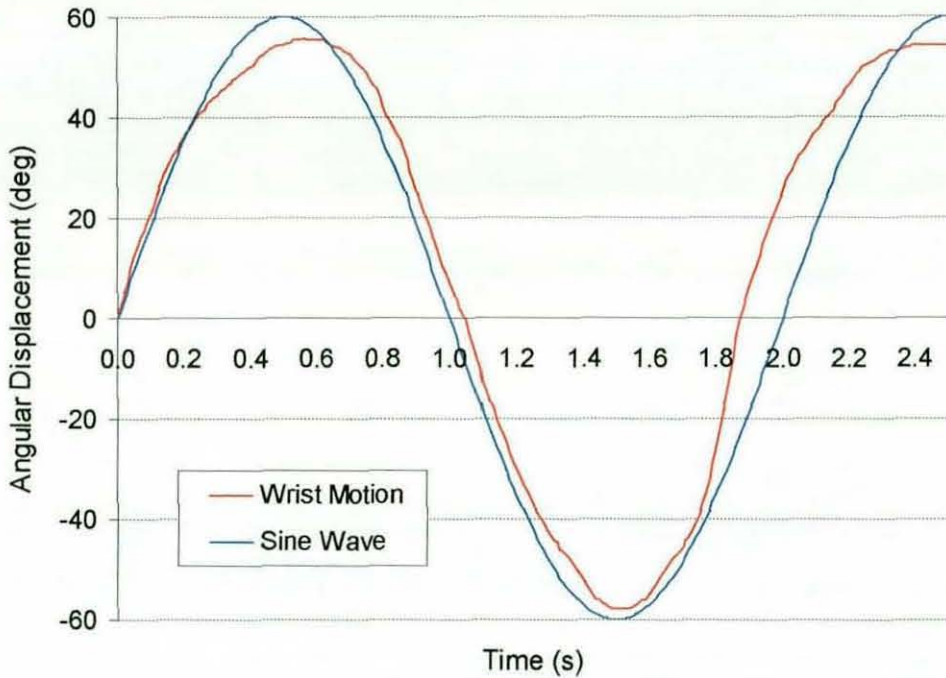
Waveforms are comprised of both an alternating and a dynamic component. To test the assumption that sinusoidal waves of a known cycle time accurately represent dynamic wrist motion of the same frequency, the waveforms were described in terms of their mathematical characteristics and compared. Descriptive characteristics of the waveforms (see Figure 37) include amplitude (A), cycle time (T) and root-mean-square value (RMS).

Figure 37: Mathematical wave characteristics
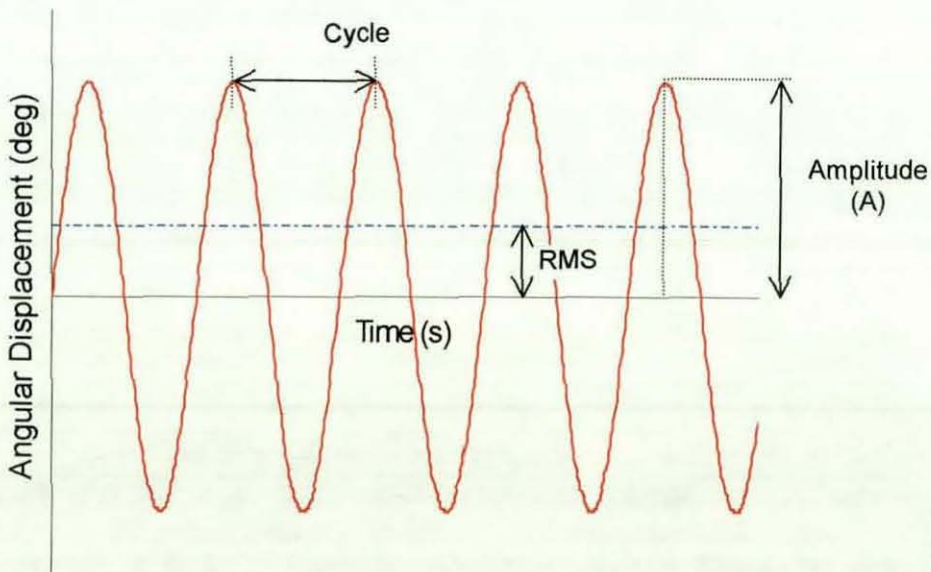
RMS is a descriptive mathematical value often used in wave mechanics to compare the dynamic component of two or more waveform signals (Equation 1).

Equation 1: <u>Calculation of root-mean-square values (RMS)</u>

$$A_{rms} = \sqrt{\frac{\sum_{i=1}^{n} A_i^2}{n}}$$

Where: A = amplitude

n = number of data points

Reasonable agreement between natural wrist motion and true sinusoidal waveforms was achieved, where reasonable agreement is defined as less than ten percent ($\pm$ 5%) difference between mathematical characteristics.

Using the sinusoidal approximation technique, mean and peak angular velocities and accelerations for sinusoidal waveforms were computed for cycle times between 20 repetitions per minute (RPM) and 50 RPM, the results of which are presented in Table 8 and Figure 38. The formulae for these derivations are as follows in Equations 2-4:

Equation 2: <u>Angular displacement of a sinusoidal wave</u>

$X = A \sin (\omega t)$

Equation 3: <u>Angular velocity of a sinusoidal wave</u>

$\delta x / \delta t = v\,(t) = A\omega \cos (\omega t)$

Equation 4: <u>Angular acceleration of a sinusoidal wave</u>

$\delta^2 x / \delta t^2 = a\,(t) = -A\omega^2 \sin (\omega t)$

<u>Where:</u> $\omega = 2\pi f$ A = amplitude

$f = 1 / T$ t = time

T = duration (cycle time)

f = frequency

Table 8: Derivatives for sinusoidal waveforms approximating repetitive wrist motion activities

RPM	Peak Displacement (degrees)	Peak Velocity (deg s⁻¹)	Mean Velocity (deg s⁻¹)	Mean Accel (deg s⁻²)	Peak Accel (deg s⁻²)	Mean Accel (rads⁻²)	Peak Accel (rads⁻²)
20	60	80.1	125.7	167.5	263.2	2.92	4.59
22	**60**	**89.5**	**138.2**	**202.7**	**318.5**	**3.54**	**5.56**
24	60	94.2	150.8	241.2	379.0	4.21	6.61
26	60	105.9	163.4	283.1	444.8	4.94	7.76
28	60	110.5	175.9	328.3	515.9	5.73	9.00
30	60	120.1	188.5	376.9	592.2	6.58	10.34
32	60	129.5	201.1	428.9	673.8	7.49	11.76
34	60	134.2	213.6	484.1	760.6	8.45	13.27
36	60	146.0	226.2	542.8	852.7	9.47	14.88
38	**60**	**150.5**	**238.8**	**604.8**	**950.1**	**10.56**	**16.58**
40	60	160.2	251.3	670.0	1052.8	11.69	18.37
42	60	169.5	263.9	738.8	1160.7	12.89	20.26
44	60	174.3	276.5	810.8	1273.8	14.15	22.23
46	60	186.0	289.0	886.2	1392.3	15.47	24.30
48	60	190.5	301.6	964.9	1516.0	16.84	26.46
49	**60**	**194.3**	**307.9**	**1005.6**	**1579.8**	**17.55**	**27.57**
50	60	200.1	314.2	1046.8	1644.9	18.27	28.71

Figure 38: Peak and mean angular accelerations of sinusoidal waveforms
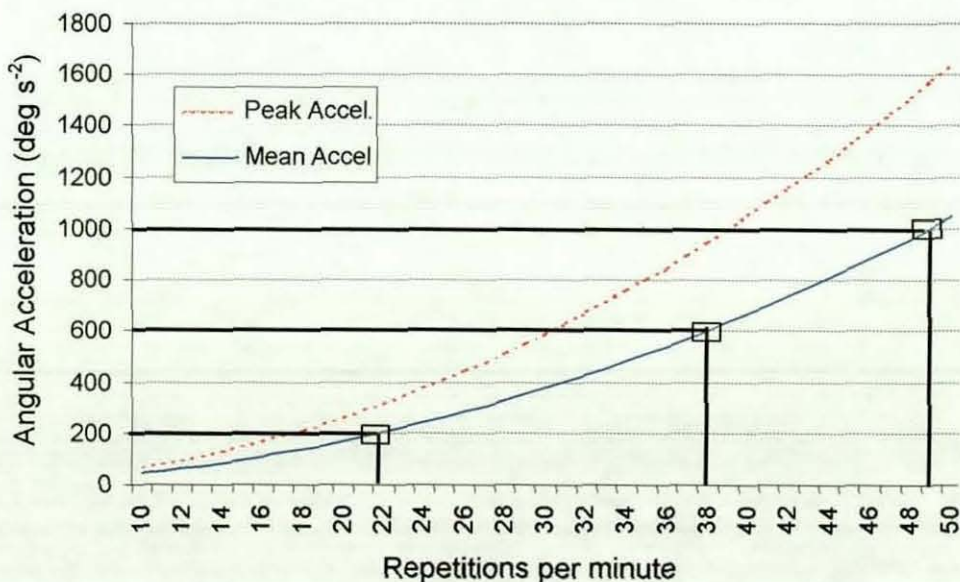
The above results indicate that repetitive wrist motions of 22, 38 and 49 RPM closely represent the desired low (200 deg s^{-2}), medium (600 deg s^{-2}) and high (1000 deg s^{-2}) wrist activity levels, respectively. Mean angular accelerations against time for each of the three selected wrist motions are compared in Figure 39, below.

Figure 39: Comparison of wrist motion waveforms
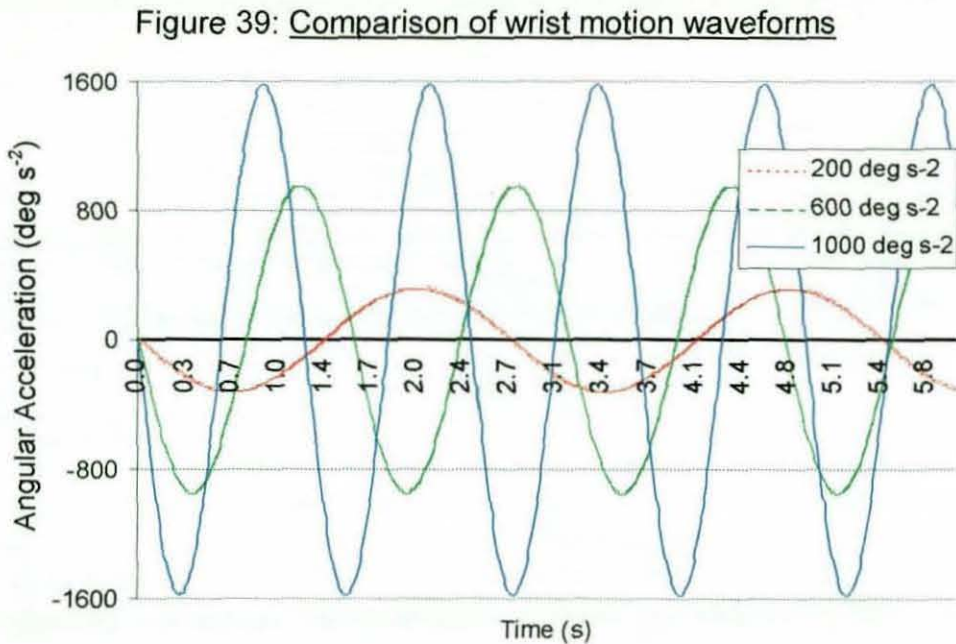
4.6 Variables

4.6.1 Independent Variables

The following independent variables were selected as measures of wrist activity, or dose:

1. *Duration of Exposure* (min) – recorded as time from task commencement.

2. *Cycle Time* (sec) - period of a single repetition

3. *Mean Angular Displacement* (deg) - average distance through which the wrist was moved during the sample

4. *Peak Angular Displacement* (deg) - maximum distance through which the wrist was moved during the sample

5. *Mean Angular Velocity* (deg s^{-1})

6. *Peak Angular Velocity* (deg s^{-1})

7. *Mean Angular Acceleration* (deg s^{-2})

8. *Peak Angular Acceleration* (deg s^{-2})

9. *Linear Force* (kgms^{-2}) - the mathematical product of mass and acceleration, where linear acceleration is computed based on the angular arc subscribed.

10. *External Work* (kgm^{2}s^{-2}) - computed as a function of force multiplied by distance traveled (d), where: W = m. accel. d

4.6.2 Dependent Variables

Consequential changes, or response, were recorded for the following dependent variables:

1. *Sensory Median Nerve Function*

   a) *Onset Latency* (msec) - Latency of the digital sensory branch of the median nerve from stimulus to response onset

   b) *Peak Latency* (msec) - Latency of the digital sensory branch of the median nerve from stimulus to peak amplitude

   c) *Duration* (msec) - Duration of evoked sensory response between onset and peak latencies

   d) *Amplitude* (mV) - Maximum amplitude of the impulse waveform

   e) *Area* (mVmsec) - Area described by evoked sensory response.

   f) *Conduction Velocity* (ms^{-1}) - stimulated nerve length divided by peak latency

2. *Perceived Subjective Comfort* - measured using the 11-point Modified Borg scale (refer to Appendix 1C).

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4.6.3 Confounding Variables

1. *Room Temperature* of the working environment in which data collection was conducted.

2. *Near-Nerve Skin Temperature* response to imposed wrist activity was measured at three anatomical sites along the digital sensory branch of the median nerve:

    a) Wrist (30mm proximal to the distal wrist crease)

    b) Hand (superficial arterial arch at the proximal palmar crease)

    c) Fingertip (on the distal phalanx of the third digit)

4.6.4 Sources of Random Error

Sources of random error might include participant demographics, subject anthropometry and medical results. After consideration of exclusion criteria, possible sources were measured but randomized through random subject selection.

4.7 Measurement

4.7.1 Questionnaire Instruments

In addition to objective measures, information was also collected using questionnaire instruments during both the medical evaluation and clinical trial phases of this study. The completion of such recording techniques is open to subjective interpretation by the participants, therefore significant consideration was given to the development of such instruments, instruction in their use, and analysis.

4.7.1.1 General Questionnaire

A general questionnaire was developed to record participant demographics. Questions pertaining to age, gender, race, dominant hand, medication use, smoking history, occupational history and participation in hand-intensive activities were included. A copy of the General Questionnaire is presented in Appendix 1A.

4.7.1.2 Health Questionnaire

A health questionnaire was developed to screen candidates for medical conditions associated with increased susceptibility to upper extremity musculoskeletal disorders. Questions concerning prior upper extremity injury, symptomatic experience of musculoskeletal disorders, history of specific diseases and illnesses, and information pertaining to reproductive health status were solicited. A copy of the Health Questionnaire is included in Appendix 1B.

4.7.1.3 Subject Comfort Survey

A comfort survey was prepared to monitor participant perception of discomfort of the dominant hand during task performance. Diagrams of the palmar and dorsal sides of the hand and wrist were presented, on which participants were encouraged to indicate their experience of pain, tingling, numbness and stiffness. In addition, a linear continuous scale (0-10) based on the 11-point linear scale (after Borg, 1982) was employed on which subjects were asked to rate their perceived comfort as it related only to their dominant hand. A copy of the Subject Comfort Survey is presented in Appendix 1C.

4.7.1.4 Anthropometry Survey

A series of anthropometric measures including height, weight, ten specific measures of dominant hand and wrist anthropometry, and pinch and power hand grip strength was cataloged as a record of participant form. A copy of the Anthropometry Survey is presented in Appendix 1D.

The techniques used to measure participant anthropometry were in accordance with guidelines set forth in the U.S. Army anthropometric survey measurer's handbook (Clauser et al, 1988). A description of each measure is presented in Appendix 1E.

4.7.2 Wrist Activity Monitoring

4.7.2.1 Description of the Measurement Technology

Wrist activity was monitored using a state-of-the-art 3D human motion tracking system, called HumanTRAC, which was developed and validated at the Center for Product Ergonomics, University of South Florida (see article presented as Attachment 6D). This technology integrates the Mannequin Professional™ computer-aided design software with Ascension Technologies' Flock-of-Birds™ electromagnetic tracking sensors.

Using this system, true 3-D coordinates of key body segment positions are streamed to a dedicated computer at up to 104 samples per second (104 Hz). Each sample includes x, y and z position coordinates, as well as yaw, pitch and roll angular measures for each body segment recorded. These positions then drive a three dimensional image of a human model, consisting of between three and five thousand polygons (Figure 40). This unique system allows the tracking of human motion directly into a computer without any manual digitizing. In brief, this method provides a very high level of fidelity in the reconstruction and analysis of 3-D human motion.

Figure 40: <u>Human motion tracking</u>

4.7.2.2 Evaluation of HumanTRAC System Accuracy

Ascension Technologies, Inc conducted an assessment of the accuracy of the hardware elements of the HumanTRAC motion-tracking system. To measure the three-dimensional linear position error of the system, one of receivers was tracked within a $16.0m^3$ volume to determine the absolute distance traversed. The receiver was attached to a programmable 3-axis platform, which was moved in 0.25mm increments using computer controlled stepping motors. Precision of the stepping platform was optically checked prior to this test and, after compensating for distortions due to floor loading, the accuracy of the platform was determined to be 0.025mm. The results (Figure 41) indicate that the root-mean-square (RMS) error for a three-dimensional linear vector measured using HumanTRAC equals 0.0015m at a transmitter to receiver distance of 2.7m. The percentage error at this distance equals 0.06%.

A similar assessment of the line-of-sight angular vector indicates that the RMS error equals 0.28 degrees at a transmitter to receiver distance of 2.7m (Figure 42).

Figure 41: Linear accuracy of HumanTRAC system
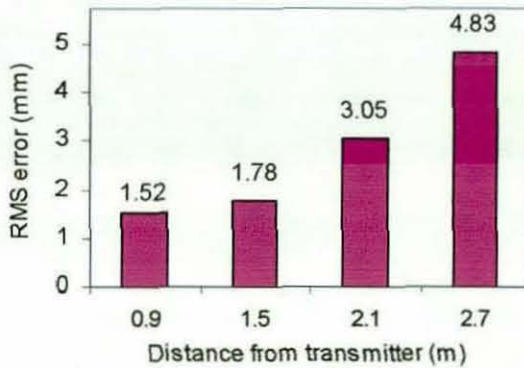
Figure 42: Angular accuracy of HumanTRAC system
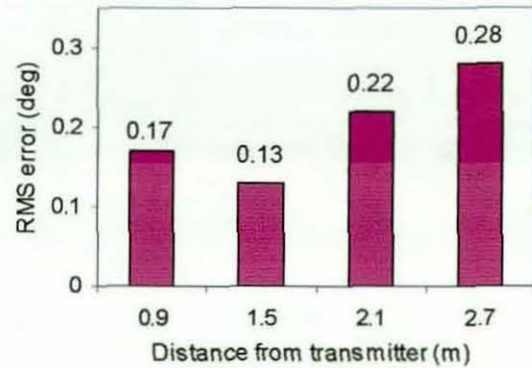
4.7.2.3 Calculation of Optimal Sampling Frequency

The prescribed activity calls for wrist movement through 240 degrees during one complete cycle. At the highest wrist activity level (1000 deg s^{-2}), estimated cycle time, based on 49 repetitions per minute is 1.22 seconds.

As discussed earlier, angular wrist displacement approximates a sinusoidal waveform (Figure 36), as defined by Equation 5.

Equation 5: Calculation of optimal sampling frequency

$$x = A \sin (\omega t) \tag{5a}$$

Where: $\omega = 2 \pi f$ A = amplitude

$f = 1 / T$ t = time

T = duration (cycle time)

f = cycle frequency

For optimal sensitivity of measures the change in angle between two consecutive sampling points should be less than 10 percent, which can also be expressed as a 90 percent ratio of angles between consecutive sampling points. The maximum time interval between consecutive points is θ. Thus, two consecutive sampling points are at times $((n+1)* \theta)$ and $(n* \theta)$. Equations 5b and 5c are transformations of equation 5a using sampling rate variables.

$$x((n+1)^* \theta) = A \sin (2.\pi.f. \theta) * x(n^* \theta) \qquad (5b)$$

$$\Rightarrow \quad x((n+1)^* \theta) / x(n^* \theta) = A \sin (2.\pi.f. \theta) \qquad (5c)$$

Where: θ = maximum time interval

                 $x((n+1)^*\theta)$ = wrist angle at data point n+1

                 $x(n^*\theta)$ = wrist angle at data point n

Solving for θ in equation 5c gives equation 5d

$$\theta = \frac{\arcsin \left[\dfrac{x((n+1)^* \theta) / x(n^* \theta)}{A} \right]}{2\pi / T} \qquad (5d)$$

For $x((n+1)^*\theta)/x(n^*\theta) = 0.90$, A = 240 degrees and T=1.22 seconds, θ = 0.042 seconds. The inverse of θ (F=1/θ) is 23.97 Hz, which is the minimum acceptable sampling rate based on the mean cycle time across participants for the high wrist activity condition. This result was confirmed graphically where difference between two consecutive points is indeed less than ten percent for a sampling frequency of 24 Hz.

Motion of the wrist was monitored at 62.55 Hz, which is the system-defined sampling frequency of the HumanTRAC motion tracking system when monitoring two receivers (two participants) simultaneously. The HumanTRAC technology is capable of monitoring motions at 104Hz for a single receiver.

Capabilities of the HumanTRAC technology satisfy sampling requirements across all conditions.

The sampling rate estimation is a crude method since the displacement curve presented in Figure 36 is not a pure sinusoidal function. However, this model does provide a rough estimate of the angular displacement path of the wrist and hence an approximation to optimal data sampling rates for wrist motion.

4.7.2.4 Wrist Activity Measurement

One electromagnetic sensor was attached to the dorsal side of each participant's dominant hand using a double-sided sticky pad (Figure 43). A simple calibration procedure required that the participant rested their dominant hand in a neutral posture for a period of two seconds each time the system was initiated. The system was activated for a period of five minutes during each hour of task performance to record wrist motion data. Data were acquired for both participants simultaneously with six degrees of freedom, including x, y, z linear and yaw, pitch, roll angular measures. The electromagnetic field generated by the HumanTRAC system caused interference with the electroneurometers. It was, therefore, not possible to acquire data from both measurement technologies simultaneously.

Figure 43: <u>Wrist activity monitoring</u>

Electromagnetic human motion sensor

A Visual Basic™ macro was written to reduce the quantity of data acquired into a manageable form (see program code in Attachment 5A). This macro was executed immediately following each data acquisition episode to verify that wrist motion data were successfully captured. The mathematical waveform characteristics were recorded into the data worksheet (Appendix 5B. Further detail of the wrist activity calculations is presented in the Data Management section 4.10.2.2 and Equations 6-16.

4.7.3 Sensory Median Nerve Function Measures

Median nerve function was monitored in accordance with practice parameters documented by the American Association of Electrodiagnostic Medicine (AAEM, 1993). Clinical faculty of the Department of Neurology at the University of South Florida, College of Medicine, provided experimenter training in electroneurometry techniques.

Sensory measures were selected as the principal quantifier of median nerve function since, as discussed earlier, sensory studies are both a direct measure of nerve function and highly sensitive to changes. The antidromic measurement technique was utilized exclusively throughout the study because the sensory nerve action potentials are large and easily distinguishable from artifact. This technique also requires lower levels of nerve stimulation and is therefore less demanding on the subject.

4.7.3.1 Electroneurometer Hardware

Sensory median nerve function was measured using a commercially available electroneurometer, which was provided by Nicolet Biomedical, Inc. (see specifications, Attachment 4A and letter of support, Attachment 4B). This medical screening tool has been appropriately tested and approved by the U.S. Food and Drug Administration (FDA) for use with human patients. The Nicolet Biomedical technology is used as the gold standard against which other diagnostic tools are compared.

The Nicolet Biomedical Compass Portabook series II™ electroneurometer consists of a base unit, a pre-amplifier, a stimulus probe and a dedicated laptop computer (Figure 44). The base amplifier, which houses a control panel, is connected to a laptop computer via the serial and parallel ports. The pre-amplifier and stimulus probe are attached to the base amplifier, to which patient stimulus, recording and grounding electrodes are connected via shielded cables. A printer may be attached to the laptop computer to print results and reports.

Figure 44: <u>Nicolet Biomedical Compass Portabook II™ electroneurometer</u>

The Nicolet Biomedical system software is hierarchical. Nerve stimulation level is adjusted by turning a dial located on the base amplifier control panel. A corresponding stimulus value is presented on the laptop computer display. Once the desired stimulus level has been set, depressing a button on the control panel produces a non-recurrent supramaximal impulse. The evoked sensory nerve response waveform is displayed on the computer monitor.

4.7.3.2 Sensory Electrode Placement

Due to the range of participant hand lengths, it was not feasible to standardize the distance (D) between the stimulus cathode and active recording electrode across all participants. Instead, placement of the stimulus cathode was standardized using anatomical landmarks. The distance (D) was recorded and held constant for all measures for each individual subject, thus permitting comparative analysis of within-subject absolute values. Nerve conduction velocity, computed as a function of peak latency and stimulated nerve length, facilitated between-subject analyses by providing a basis for comparison.

All skin 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 the electrodes.

An active ring electrode (negative) was applied immediately below the head of the proximal phalanx on the subject's third digit (middle finger), which lies within the sensory median distribution. The reference ring electrode (positive) was positioned immediately below the head of the middle phalanx on the same finger, distal to the active electrode. A large ground electrode was placed on the dorsum of the hand. To further reduce any effect of artifact, a second ground electrode was applied over the pisiform bone (ulnar side of wrist at distal wrist crease).

A mark was made on the subject's forearm 30mm proximal to the distal wrist crease (where the distal wrist crease coincides with the proximal edge of the transverse carpal ligament), which was used as a reference for placement of the stimulus cathode (negative). A stimulus bar electrode was placed along the centerline of the forearm between the flexor pollicis longus and flexor digitorum superficialis of the middle finger, with the stimulus cathode proximal to and stimulus anode distal to the carpal tunnel (refer to Figure 45).

Figure 45: <u>Sensory electrode placement</u>
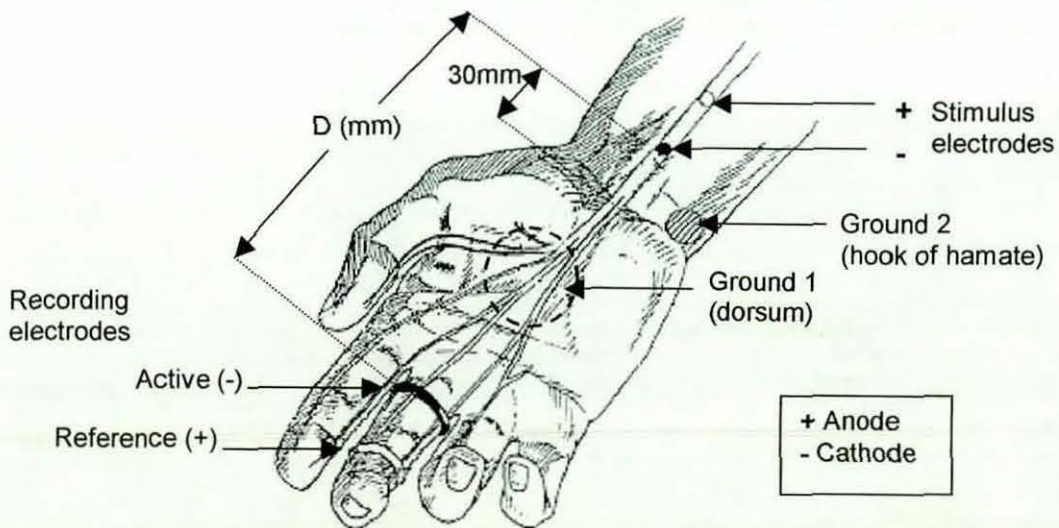
Disposable electrodes, which were used throughout the study, afforded two advantages. Firstly, participant hygiene was protected, and secondly, variability of electrode gel application was controlled since the disposable electrodes were pre-gelled.

Electrode placement was strictly controlled by marking initial locations with a permanent ink pen to ensure within-subject repeatability in the event that electrodes were changed.

4.7.3.3 Sensory Median Nerve Function Measurement

Stimulus level was determined for each participant at the start of data collection. This was achieved by incrementally increasing and reapplying a stimulus antidromically along the median nerve fibers, until a clearly defined sensory response of amplitude between 20 μV and 40 μV was produced. The resultant waveform of median nerve evoked sensory response was recorded as the baseline measure (T=0). Baseline stimulus level was maintained across within-subject measures unless median sensory response deteriorated and was difficult to distinguish from artifact.

Software algorithms automatically processed nerve function measures, including onset and peak latencies, duration of impulse, impulse amplitude, and area under the waveform for the digital sensory branch of the median nerve (Figure 46).

Figure 46: <u>Electroneurometry measures of sensory median nerve function</u>
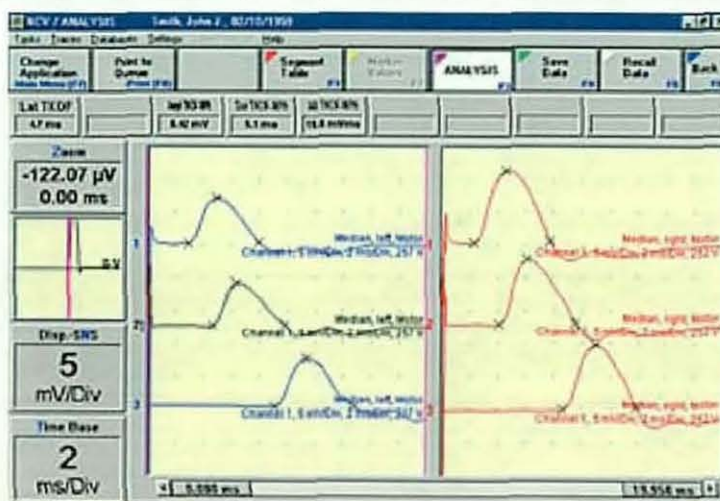
Sensory median nerve function measures were recorded immediately preceding task commencement and every ten minutes thereafter during task performance. To minimize the effect of muscle artifact, participants were asked to pause and rest their dominant hand/wrist in a neural posture for a

period of two seconds while sensory median nerve response was evoked. Results were recorded both in hardcopy and to the data collection worksheet (Appendix 5B) for later analysis.

4.7.4 Monitoring of Covariates

4.7.4.1 Room Temperature

The environment in which data collection was conducted was thermostatically controlled between 23 and 25°C (73-77°F), which is a typical office temperature in Florida. Adherence to this control was monitored with 0.5°C precision and recorded hourly from a wall-mounted mercury thermometer adjacent to subject B workstation (Figure 49). Effects of air velocity were considered negligible in the closed environment.

4.7.4.2 Near-Nerve Skin Temperature

The correlation between median nerve function and near-nerve skin temperature is widely documented. In accordance with practice parameters for electrodiagnostic studies in carpal tunnel syndrome, published by the American Association of Electrodiagnostic Medicine (AAEM, 1993), skin temperature was monitored along the median nerve proximal to the transverse carpal ligament. A minimum skin temperature of 31°C (88°F) at this site is necessary to produce reliable findings of median nerve function (Jackson and Clifford, 1989).

Measures were recorded immediately preceding the commencement of task performance and every twenty minutes thereafter using Sharin, Inc.'s DermaTherm™ perfusion monitors, with 0.5°C (1.0°F) precision (Figure 47). The temperature sensitive area of the electrode is reasonably shielded from environmental effects by adhesive insulated edges.

Figure 47: Skin temperature electrode

Empirical evidence discovered during data collection with the first three subjects revealed that while minimum skin temperature requirements for the proximal nerve were satisfied, skin temperature distal to the transverse carpal ligament appeared to be somewhat cooler. Data collection protocol was modified to further explore this observation by including two additional skin temperature-monitoring sites along the distal digital sensory fibers of the median nerve (Figure 48).

Figure 48: Near-nerve skin temperature measures
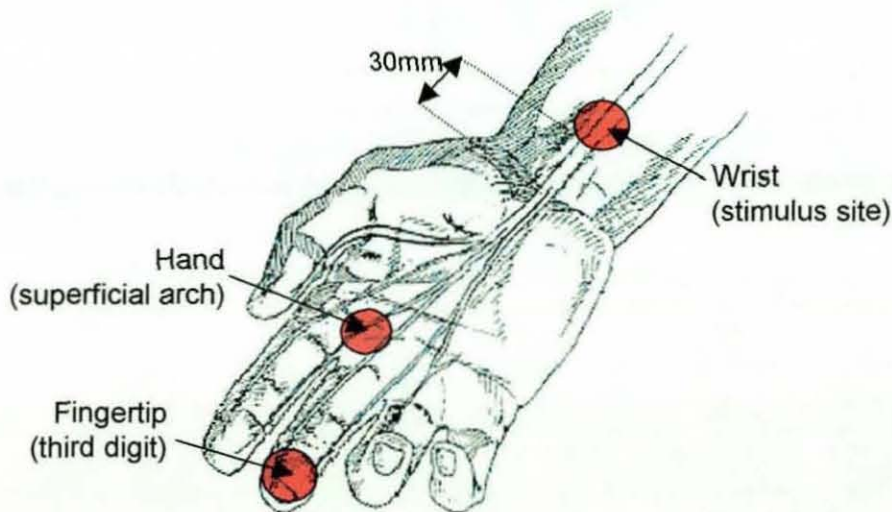
4.8 Description of the Site

Data collection was performed in the research laboratory of the Center for Ergonomics, located at the University of South Florida, College of Public Health. The laboratory contains seat pressure assessment technology, computer-based electromyography, data gloves to track 3-D hand motion, and a unique electromagnetic whole-body motion tracking system (HumanTRAC) as the front end for a powerful human computer-aided-design system.

4.8.1 Laboratory Setup

Two subject workstations were setup in the research laboratory with a temporary office partition between the stations to prevent the participants from viewing each other's task. The partition also served to discourage interaction between participants, which might disrupt task performance (Figure 49).

Figure 49: <u>Clinical laboratory setup</u>
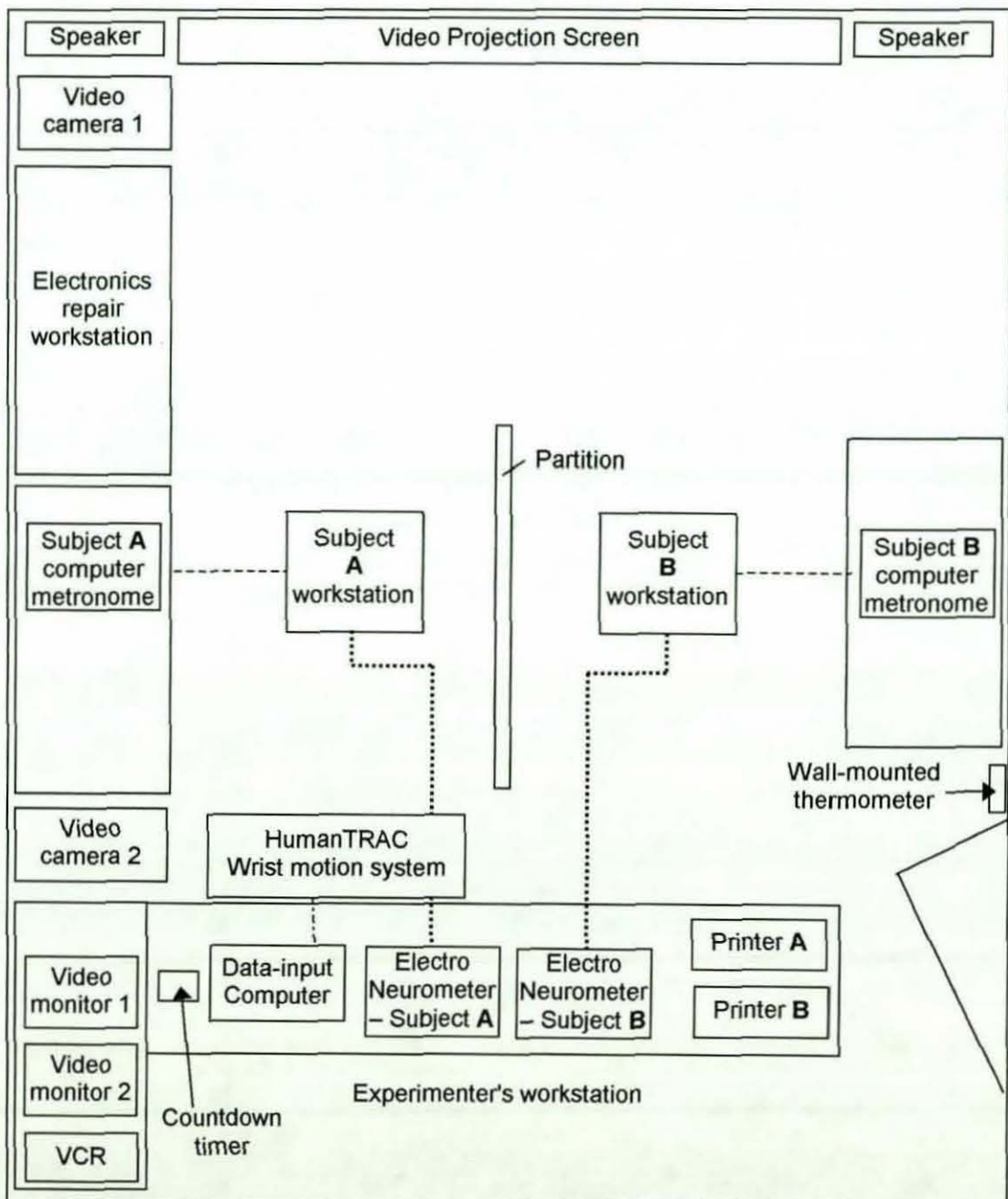
Alongside each workstation was a desktop computer that presented simultaneous audible and visual task execution stimuli to the participants. A visual stimulus, in the form of a software-animated metronome, was constantly visible on the computer monitor, which was oriented toward the respective participant. The audible stimulus was presented as a repetitive beat via headphones that were worn by the participants. The headphones shielded the audible stimuli from colleagues who may be operating at different task frequencies, as dictated by the task randomization schedule (Appendix 5A).

Video cameras mounted along one wall of the laboratory provided visual feed to two video monitors situated at the experimenter's workstation, which allowed supervision of the participant's performance without physical interference. The video cameras also provided input to a VCR at the experimenter's workstation to permit recording of the data collection process for documentation purposes.

Subject entertainment, in the form of documentary videos, was presented via the video projection screen and adjacent audio speakers.

4.8.2 Experimenter's Workstation

The experimenter's workstation was designed to facilitate data collection with a minimal level of interaction with the participants (Figure 50). The HumanTRAC 3D electromagnetic human motion tracking system, located directly in front of the experimenter's workstation was used to monitor wrist activity. Two Nicolet Biomedical Compass Portabook electroneurometers, one dedicated system per subject, were also located at the experimenter's workstation, which were used to measure sensory median nerve function at predetermined regular intervals throughout the workday. A countdown timer on the experimenter's desk served to remind the investigator precisely when each nerve measurement was due.

Figure 50: <u>Experimenter's workstation</u>

Countdown timer

Video monitors

VCR

Electro neurometer

Video camera

HumanTRAC motion tracking system

Workstation partition

Printer

4.8.3 Subject's Workstation Design

A seated workstation was designed for optimal participant comfort. Ergonomic office task chairs served as the basis for the workstation. The top of the dominant armrest was removed and replaced with a simple upper extremity workstation. Armrest mechanisms were retained and provided workstation height and width adjustability to accommodate a typical range of adult occupants. The non-dominant armrest was also removed to facilitate ingress / egress without risk of damaging the workstation. Chair casters were wrapped with cloth to prevent mobility and thus reduce the risk of over-stretching the electroneurometer cables. A standard office footrest was provided to promote subject comfort (Figure 51).

Three such workstations were constructed, including two right-handed and one left-handed workstation to accommodate most any permutation of participants.

Figure 51: <u>Subject's workstation</u>

Representative of a
50th percentile US adult
female participant

Dominant upper
extremity
workstation

Immobilized
casters

Footrest
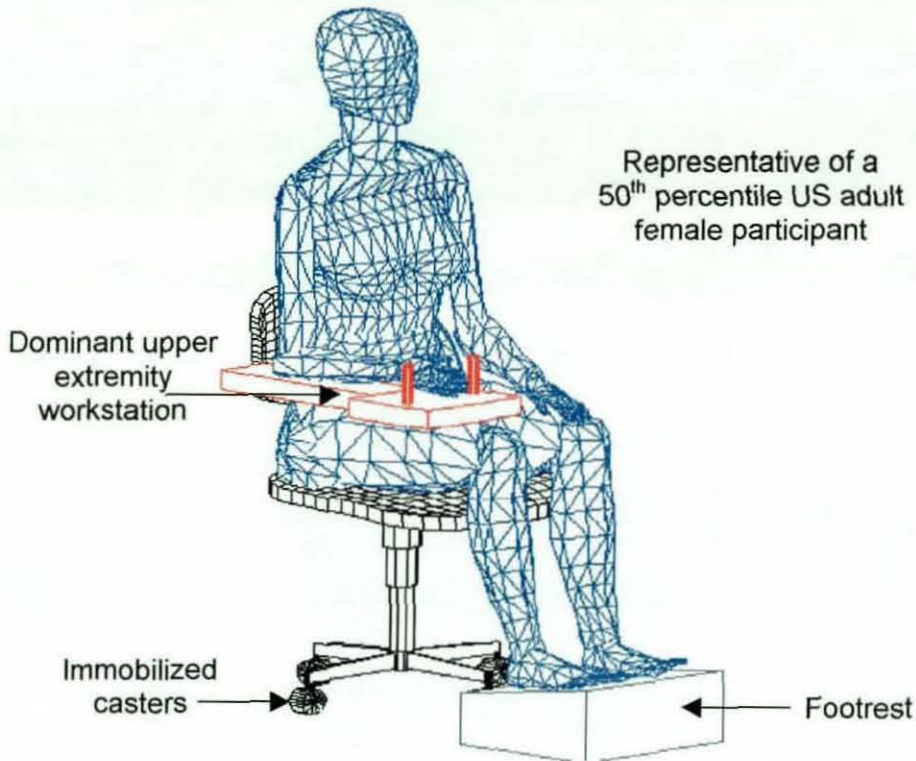
A gel-filled computer wrist rest was used to support the subject's upper extremity in a neutral posture. A padded strap was used to maintain forearm position during wrist motion with minimal risk of soft tissue compression. Physical markers were added to the workstation, which mapped out an arc of 120 degrees about neutral to provide angular displacement feedback to the participant (Figure 52).

Figure 52: <u>Upper extremity workstation</u>

Electroneurometer
electrodes

Dominant arm
supported and
secured

Gel-filled wrist
rest

Physical
marker

120°

Repetitive
flexion/extension in
horizontal plane
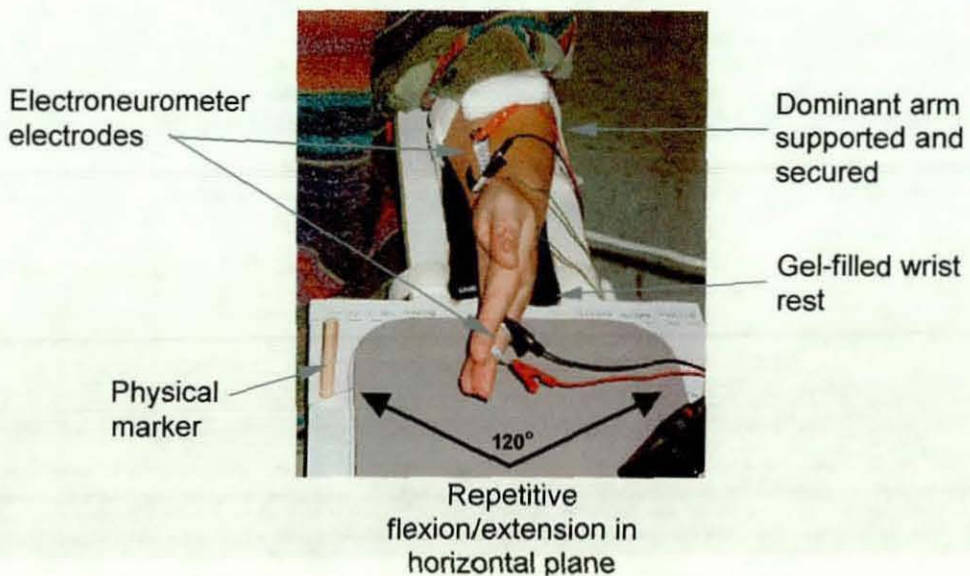
4.8.4 Participant Entertainment

Due to the monotony of the task it was considered necessary that some form of entertainment be provided, otherwise an unacceptable level of subject attrition might have resulted.

Significant consideration was given to this detail, since if the level of entertainment was uninteresting the subject may experience boredom and complacency. Conversely, if too exciting the subject may produce irregular motions. Furthermore, one of the objectives of this study was to investigate the strength of agreement between objective and subjective findings. Therefore, it was imperative that subjective recordings not be confounded by the participant's measure of enjoyment of a particular movie.

Given the above considerations, a library of audio-visual documentaries pertaining to nature, wildlife, history and similar subjects were acquired on videocassette. These videos were played throughout the data collection procedure. Presentations were balanced across participants.

While difficult to calculate the true impact of the selection, it is felt that a reasonable accommodation of participants' needs was effectively provided without compromising the validity of recorded measures.

4.9 Data Collection Protocol

A data collection protocol was established to standardize methods of data collection between subjects and so minimize experimenter-induced variability. The data collection checklist was displayed at the experimenter's workstation for ease-of-reference (Appendix 5C).

Participants were welcomed at the University of South Florida's College of Public Health in Tampa, Florida at the start of the workday. A bathroom break was suggested prior to entering the ergonomics laboratory to avert interruptions. Workstations were randomly assigned to the attending participants. The investigator then assisted each subject with adjustments to their workstation and task chair for optimal comfort. The participant's dominant upper extremity was properly oriented on the workstation with the forearm

positioned in the horizontal plane and cushioned on a gel-filled support. The thumb was oriented uppermost such that flexion-extension motion was performed in the horizontal plane. Gravitational effects between flexion and extension wrist deviations were thus equalized. A padded Velcro™ strap, which served more as a psychological than physical restraint, was positioned across the subject's forearm to minimize arm motion during task performance.

Power to all data collection systems, including video cameras and monitors, audio-visual projection equipment, HumanTRAC wrist motion system and Nicolet Biomedical electroneurometers was turned on. A computer file directory in the name of each participant was created on the dedicated electroneurometer computers where data specific to that subject's sensory median nerve function was recorded and logged by time of day.

Disposable electroneurometer electrodes were applied to the participant's dominant hand and wrist consistent with the technique explained in section 4.7.3.2. Recording cables attached to the middle finger were secured using medical adhesive tape to prevent movement during task performance. One electromagnetic sensor from the HumanTRAC human motion tracking system was placed on the dorsum of the dominant hand about the center of mass of the hand and attached using double-sided adhesive pads.

Setup of the Nicolet Biomedical electroneurometer was tested by zeroing the stimulus level on the base amplifier and depressing the stimulus switch button. A straight-line graphic response indicated correct electrode application and satisfactory system operation. A desirable stimulus level was then determined for each participant as described in section 4.7.3.3, and the resulting waveform response recorded as baseline measure of nerve function.

Since median nerve response may be affected by environmental conditions, twenty minutes was allowed during experiment setup for the subjects to adapt to the laboratory environment.

Detailed instructions (see Appendix 5D) were read to the participants each day immediately preceding task commencement. The instructions included a 'Stopping Rule', which explained to the subject's that their participation was voluntary and, if at any time they were unable to continue, that they may be excused from the study at their own request.

Participants were required to perform repetitive flexion-extension motions of the hand/wrist, during which an angle of 120 degrees was subtended about the neutral position. Angular displacement feedback was provided to the subjects by means of physical markers located on the upper extremity workstation.

Four levels of wrist activity, expressed as mean angular accelerations of the wrist, corresponding with six hours at 0 deg s^{-2}, two hours at 200 deg s^{-2}, four hours at 600 deg s^{-2} and six hours at 1000 deg s^{-2}, defined as static, low, medium and high wrist activity, were prescribed based on task frequency. Task assignment was randomized using the task randomization table presented in Appendix 5A. Tasks were performed on non-consecutive days, allowing a one-day break between workdays for physiological recovery.

Wrist activity was recorded for five minutes during each hour of task performance using the electromagnetic human motion tracking system. Sensory median nerve function was measured at the beginning of each session and at ten-minute intervals throughout task performance. Near-nerve skin temperature was recorded every twenty minutes at three sites along the digital sensory fibers of the median nerve. Subjects were also asked to rate their dominant hand comfort level, using an 11-point modified Borg scale, at the beginning of the workday and after each hour of task performance.

Two 2-hour segments were completed in the morning and one in the afternoon. Appropriate rest and lunch breaks were provided consistent with a typical workday (see Figure 53).

Figure 53: Data collection timeline

Task	Duration	8am	9am	10am	11am	12noon	1pm	2pm	3pm	4pm
Median nerve warm up	30 min									
Preparations	15 min									
Baseline measures	15 min									
Session 1	2 hours									
Morning break	15 min									
Setup following break	15 min									
Session 2	2 hours									
Lunch break	30 min									
Setup following break	15 min									
Session 3	2 hours									
Conclusion measures	15 min									

Results were reported in tabular format, by subject, for subsequent analysis (refer to Data Collection Worksheet in Appendix 5B).

4.9.1 Pilot Study

A pilot study was performed prior to commencement of the clinical trial. The purpose of the pilot study was to evaluate and refine the data collection procedure, and to perform a preliminary investigation of outcome measures for use in the sample size power analysis. Subjective comments were also solicited to learn if stressors imposed on the upper extremity induced excessive discomfort, or if the participant's experience could be reasonably improved.

One asymptomatic female participant was recruited for the pilot study, whose demographics were similar to those of the study group. The pilot subject was required to complete two 2-hour sessions, with a thirty-minute recovery period between sessions. A task repetition rate of 49-RPM (1000 deg s^{-2}) was selected for both sessions, as it was assumed that the highest task repetition would impose the greatest biomechanical stress.

Data Collection protocol, as previously documented, was strictly adhered to. The sole exception was that nerve conduction testing was performed every five minutes to determine if repeated supramaximal stimulation of the participant's median nerve proved too uncomfortable.

Absolute data for median nerve sensory function during sessions 1 (S1) and 2 (S2) are presented below in Figures 54 through 57.

Figure 54: <u>Sensory latency values, S1</u> Figure 55: <u>Sensory latency values, S2</u>

— Onset latency   — Peak latency
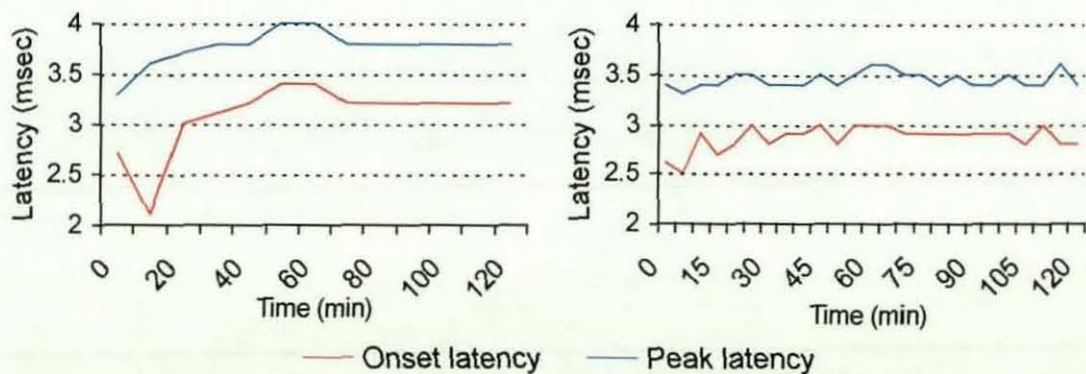
Figure 56: Sensory amp & area, S1   Figure 57: Sensory amp & area, S2
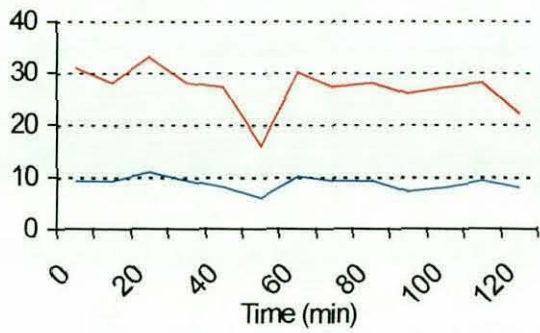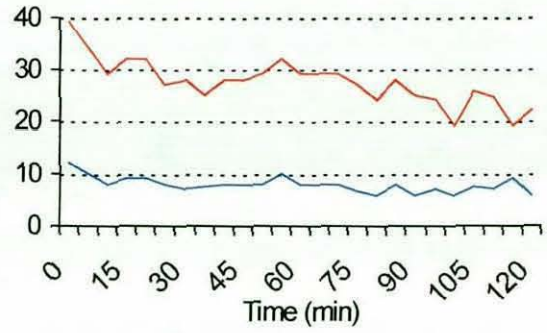
— Amplitude (µV)   — Area (µVms)

Percent change of sensory median nerve function with respect to the baseline measures is summarized in Tables 9 and 10.

Table 9: Percent change for pilot nerve function measures, session 1

% Change	Onset Latency	Peak Latency	Amplitude	Area
Maximum	+25.9	+21.2	+7.2	+34.5
Minimum	-22.2	0.0	-50.5	-40.5
At Session End	+18.5	+15.2	-29.3	-22.6

Table 10: Percent change for pilot nerve function measures, session 2

% Change	Onset Latency	Peak Latency	Amplitude	Area
Maximum	+15.4	+5.9	0.0	0.0
Minimum	-3.8	-2.9	-52.9	-52.8
At Session End	+7.7	0.0	-41.9	-52.8

With respect to the baseline measure (T=0), results indicate that onset and peak latencies increased throughout task performance, while amplitude of axon excitation and area under the waveform decreased. A conservative effect size of ten percent was chosen for use in the sample size power calculation based on these findings.

At the conclusion of the pilot study, an informal discussion was held with the participant. It was discovered that repetitive nerve stimulation did not produce excessive discomfort, even when performed every five minutes. The

participant described an occasional sensation of tingling in the sensory median nerve distribution, which quickly dissipated when the activity ended. This was noted as temporary symptomatic experience of mild median nerve neuropathy and was consistent with recorded changes in median nerve function.

Follow-up consultation with the pilot subject indicated that she had not experienced any further symptoms. It was therefore assumed that the subject had recovered quickly and completely from physical stresses imposed on the dominant upper extremity.

4.10 Data Management

Data were categorized across participants into measures of sensory median nerve function, wrist activity, room temperature, near-nerve skin temperature, subjective comfort, and participant demographic, anthropometric and medical results. Within these categories, the data were further grouped according to condition (static, low-AM, low-PM, medium-AM, medium-PM and high) and reported on a timeline.

4.10.1 Sensory Median Nerve Function Data

Sensory median nerve function data files were prepared across participants for measures of stimulus level, onset latency, peak latency, duration, amplitude, area and conduction velocity, where conduction velocity was determined as a function of sensory peak latency and nerve length.

4.10.2 Wrist Activity Data

Linear and angular measures of wrist displacement were derived from positional data acquired using the HumanTRAC 3D motion tracking system. Advantages of this technology include the availability to directly record data

into a computer. Furthermore, system calibration was straightforward and the technology was readily available. A disadvantage of this measurement technology lies in acquisition of relational joint angles rather than absolute values. However, since the position of the dominant forearm was fixed and wrist position was neutral during calibration, relational data is equivalent to absolute joint angles of the wrist.

4.10.2.1 Digital Signal Processing

The raw joint angle data were suspected to contain additive noise data from random sources. The presence of higher frequency noise is of particular importance when calculating velocities and accelerations, since the amplitude of each of the harmonics is known to increase with its harmonic number. For velocities the increase is linear, while for accelerations the increase is proportional to the square of the harmonic number. Suspicions were confirmed in plots of raw angular velocity and acceleration data (Figure 58).

Figure 58: <u>Velocity and acceleration derivatives of raw joint angle data</u>
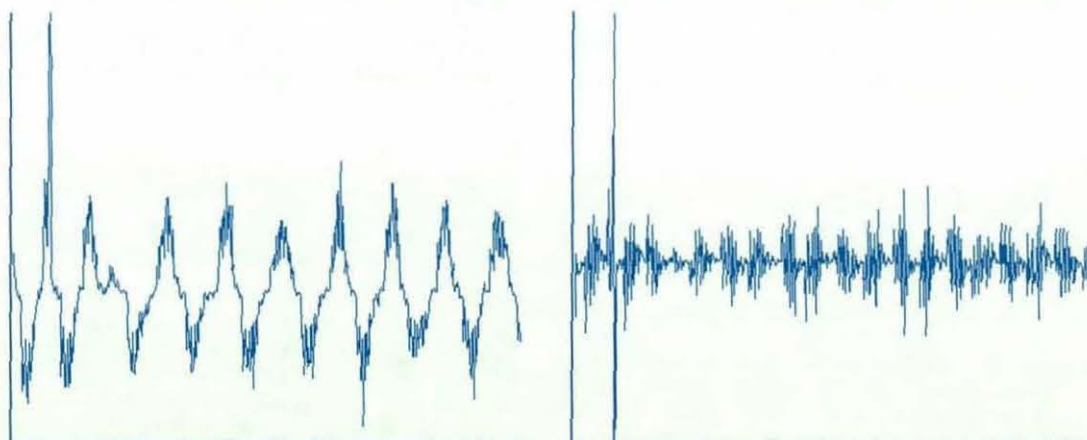
Fast Fourier transform (FFT) analysis was performed to identify frequencies associated with the true data and random noise data (Figure 59).

Frequencies of the true data were found between 1.0 and 4.0 Hz, consistent with cycle frequencies of the prescribed wrist motions. While the magnitude of higher frequencies of random data was minor, the effect of those noise data masked derivative kinematic measures of wrist motion, as described.

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Figure 59: Fast Fourier transform analysis
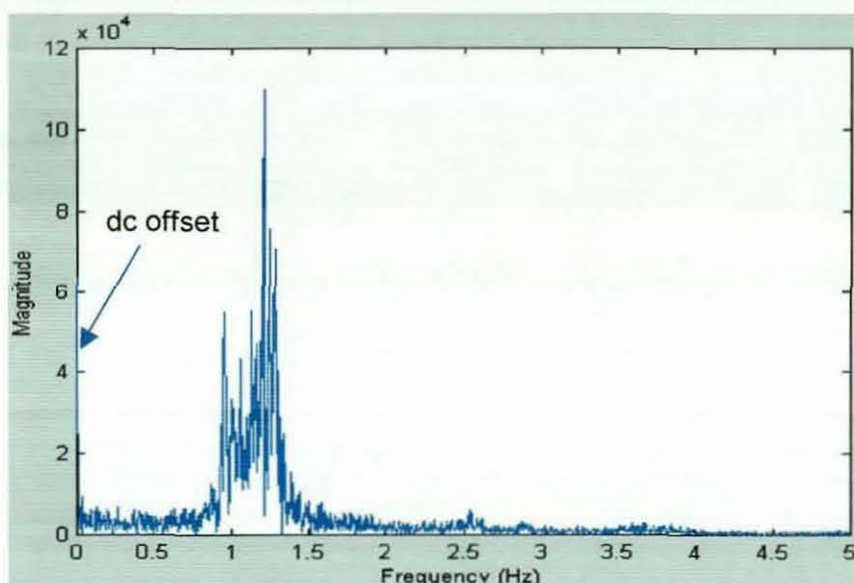
Using MatLab (version 5.3), a Butterworth low-pass filter was developed to attenuate the higher frequency noise (Figure 60). A fourth-order filter was selected to sharpen the filter cutoff frequency. Since cycle frequencies varied both between and within subjects as well as between conditions, frequency response of the filter was computed as a function of the frequency of the wrist motion data. Programming for this filter is presented in Attachment 5B.

Figure 60: Butterworth fourth-order low-pass filter
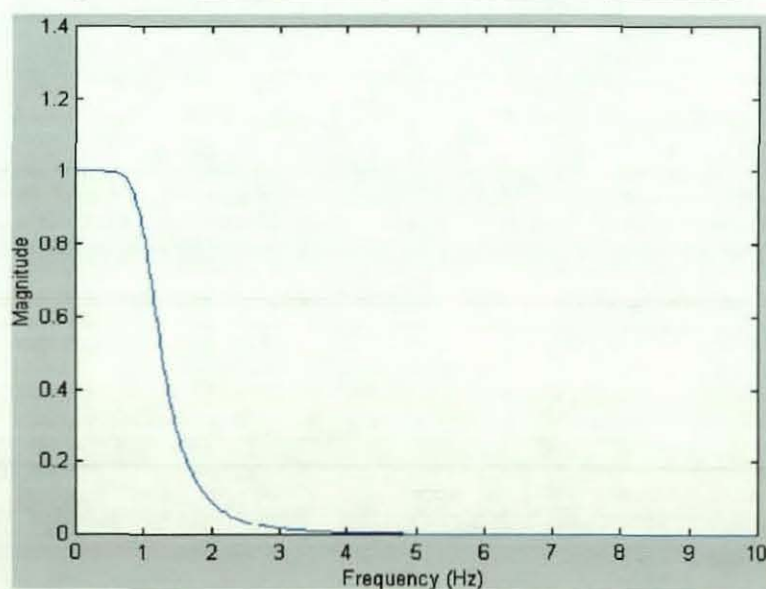
The effectiveness of this filter in attenuating higher frequency sources, while preserving the integrity of wrist motion data is illustrated in figure 61.

Figure 61: Data filtering process
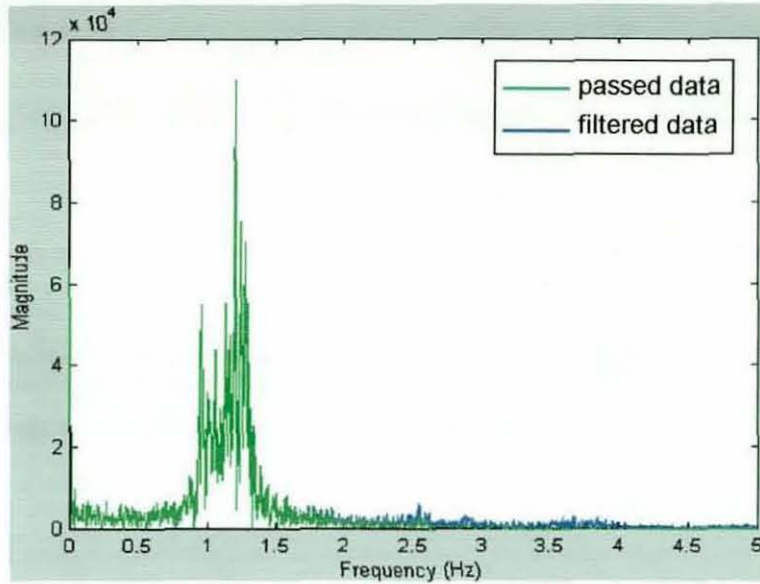
After filtering effects of random noise data from wrist motion samples, derivative measures of angular velocity and acceleration were revisited (Figure 62). Phase translation evident in the filtered derivative measures was expected to have no consequence on subsequent analyses.

Figure 62: Comparison of filtered and unfiltered kinematic measures
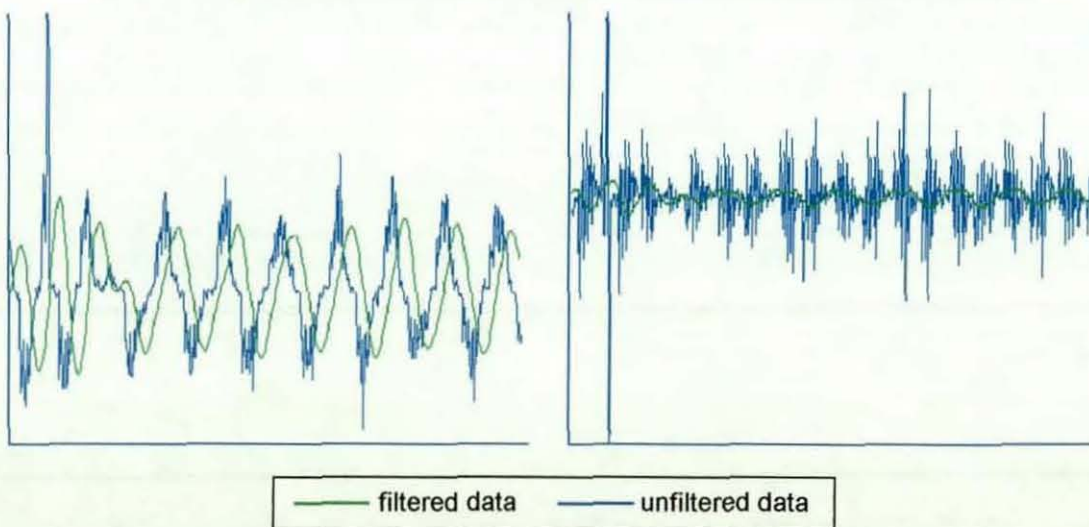
4.10.2.2 Kinematic Derivatives of Wrist Activity

The prescribed activity required that motions of the wrist be performed in the flexion-extension plane. Subject workstations were designed to support this specific activity. Nevertheless, it was discovered that minor radial-ulnar and pronation-supination components of wrist motion were evident in the data.

Thirteen kinematic measures of wrist activity were calculated for each of three planes of motion from filtered angular displacement data (Equations 6 through 16). The root-mean-square value of the combined elements was then computed for each participant and condition. A key to all variables is presented following Equation 16.

(i) Cycle Time (s)

Equation 6: Calculation of cycle time

$$CT = \frac{60}{RPM}$$

(ii) Mean Angular Displacement (deg) – positive and negative

Equation 7: Calculation of mean angular displacement

$$\overline{x}.disp = mean[x]_{i=1}^{n}$$

(iii) Peak Angular Displacement (deg) – positive and negative

Equation 8: Calculation of peak angular displacement

$$peak.disp = \max[x]_{i=1}^{n}$$

(iv) Mean Angular Range of Motion (deg)

Equation 9: Calculation of mean angular range of motion

$$\overline{x}.range = \max[x]_{i=1}^{n} + |\min[x]_{i=1}^{n}|$$

(v) Peak Angular Range of Motion (deg)

Equation 10: Calculation of peak angular range of motion

$$peak.range = \max[x]_{i=1}^{n} + |\min[x]_{i=1}^{n}|$$

(vi) Mean Angular Velocity (deg s^{-1})

Equation 11: Calculation of mean angular velocity

$$\bar{x}.vel = \frac{\sum_{i=1}^{n} \delta x / \delta t}{n}$$

(vii) Peak Angular Velocity (deg s^{-1})

Equation 12: Calculation of peak angular velocity

$$peak.vel = \max |\delta x / \delta t|_{i=1}^{n}$$

(viii) Mean Angular Acceleration (deg s^{-2})

Equation 13: Calculation of mean angular acceleration

$$\bar{x}.accel = \frac{\sum_{i=1}^{n} \delta^2 x / \delta t^2}{n}$$

(ix) Peak Angular Acceleration (deg s^{-2})

Equation 14: Calculation of peak angular acceleration

$$peak.accel = \max |\delta^2 x / \delta t^2|_{i=1}^{n}$$

(x) Linear Force (kgms^{-2}) (see also Figure 63)

Equation 15: Calculation of linear force

$$F = m \times a$$

$$m = \overset{*}{\vartheta} \times V$$

$$a = \iint arc \cdot of \cdot motion$$

$$arc \cdot of \cdot motion = radius \cdot of \cdot curvature \times ratio\left(\frac{arc \cdot subscribed}{circumference}\right)$$

$$\therefore arc \cdot of \cdot motion = \left(\frac{2 \times A_{range}}{360}\right) \times 2\pi \overset{**}{r}_{COM}$$

$$r_{COM} = HL \times 49.4\%$$

$$\therefore F = (\overset{*}{\vartheta} \times V) \times \iint\left[\left(\frac{2 \times A_{range}}{360}\right) \times 2\pi(HL \times 49.4\%)\right]$$

Figure 63: Derivation of arc of motion
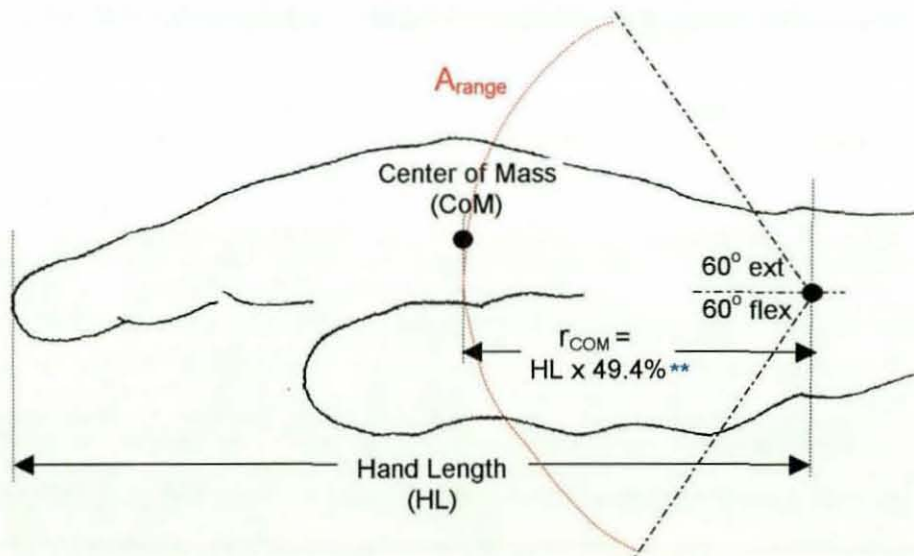
* Hand density constant (1.16 g/cm^3) (Dempster, 1955)

** Location of center of mass after Dempster (1955)

(xi) Cumulative Work Performed (kgm^{2}s^{-2})

Equation 16: Calculation of cumulative work performed

$$W = F \times d$$

$$F = (\vartheta \times V) \times \iint \left[\left(\frac{2 \times A_{range}}{360} \right) \times 2\pi (HL \times 49.4\%) \right]$$

$$d = \left(\frac{arc \cdot of \cdot motion}{time \cdot interval} \right) \times T$$

$$time \cdot interval = \frac{CT}{60}$$

$$\therefore W = (\vartheta \times V) \times \iint \left[\left(\frac{2 \times A_{range}}{360} \right) \times 2\pi (HL \times 49.4\%) \right] \times \left[\frac{\left(\frac{2 \times A_{range}}{360} \times 2\pi (HL \times 49.4\%) \right)}{\left(\frac{CT}{60} \right)} \right] \times T$$

Where:

x = angular displacement

$\overline{x}$ = mean angular displacement

n = number of data points

W = work

F = force

d = distance

m = mass

ϑ = density of hand
(after Dempster, 1955)

a = linear acceleration

T = duration of exposure

RPM = repetitions per minute

V = hand volume

A $_{range}$ = amplitude range

HL = hand length

CT = cycle time

r $_{com}$ = radius of curvature to center
of mass of hand

In all, fifty-two kinematic measures of filtered wrist motion were referred for subsequent analysis.

CHAPTER 5: RESULTS

Results of this study are presented in the following order: (1) wrist activity, (2) sensory median nerve function, (3) subjective comfort, (4) room temperature, (5) near-nerve skin temperature. Absolute data pertaining to the above independent, dependent and confounding variables are presented in Appendix 6.

5.1 Wrist Activity

Wrist activity measures were calculated across participants for each condition. Thirteen independent variables describing wrist activity were computed for each plane of motion (flexion-extension, radial-ulnar, pronation-supination) (refer to Appendix 6A). Root-mean-square values across planes of wrist motion are presented in Table 11.

Table 11: <u>Summary of wrist activity measures</u>

Parameter	Static		Low		Medium		High	
	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
Cycle Time	0.00	0.00	2.34	0.27	1.37	0.16	1.07	0.07
Mean Flexion	0.00	0.00	44.30	9.00	44.42	8.25	43.57	7.86
Peak Flexion	0.00	0.00	59.21	11.32	59.37	10.26	59.25	10.36
Mean Extension	0.00	0.00	42.17	9.10	42.40	6.88	41.16	8.46
Peak Extension	0.00	0.00	56.12	12.19	56.52	10.25	55.45	11.62
Mean Range	0.00	0.00	86.07	12.18	86.09	9.63	84.08	11.15
Peak Range	0.00	0.00	114.32	16.30	114.30	13.98	113.24	16.03
Mean Velocity	0.00	0.00	73.99	13.87	125.88	18.76	156.30	24.07
Peak Velocity	0.00	0.00	155.15	29.18	276.17	41.54	347.99	57.96
Mean Accel	0.00	0.00	212.43	72.53	609.68	117.81	953.74	185.20
Peak Accel	0.00	0.00	527.94	187.85	1660.81	358.35	2562.21	601.74
Force	0.00	0.00	0.016	0.006	0.047	0.012	0.075	0.022
External Work	0.00	0.00	7.80	4.63	57.80	34.47	68.18	36.15

Mean cycle times across subjects for low, medium and high wrist activity conditions were 2.34, 1.37 and 1.07 seconds per repetition, respectively. Cycle times were similar between ordered conditions and between sessions, indicating that participants maintained a similar task frequency throughout each prescribed workload level. Expressed in repetitions per minutes, task frequencies compare to 25.6, 43.8 and 56.1 RPM, respectively. Overall, prescribed frequencies were exceeded by approximately 15 percent.

Mean and peak angular displacements across participants were comparable across conditions. Positive displacement (i.e. flexion) was favored slightly over negative displacement, which is typical, owing to a slight palmar tilt of the distal radial plates (Sarrafian et al., 1977). Across participants and conditions, mean range of motion (171 degrees per cycle) was within normal ranges, but approximately 29 percent less than the prescribed displacement.

Figure 64 illustrates the cumulative and total workload performed under each condition and each combination of conditions.

Figure 64: <u>External work across sessions, by condition</u>
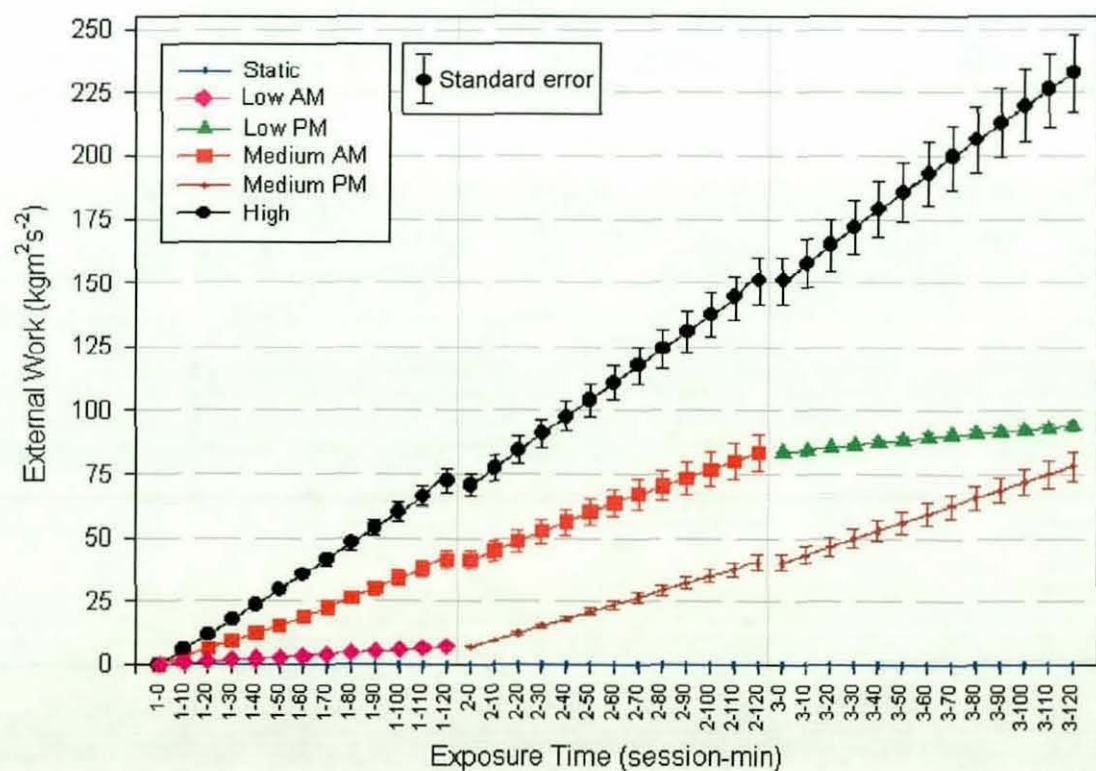
Total work performed under the moderate-AM / low-PM schedule is approximately 15 percent more than the similar low-AM /moderate-PM assignment. This observation suggests a possible training effect between varied workload levels performed on the same day, where the learned repetition rate of the first task influences performance of a subsequent task.

Using work as the comparative measure between planes of motion, it was discovered, across participants and conditions, that 88.9 percent of wrist activity was performed in the flexion-extension plane. Ulnar-radial and pronation-supination planes accounted for 4.6 and 6.5 percent of wrist motion, respectively.

5.2 Sensory Median Nerve Response

Antidromic measures of sensory median nerve function (SMNF) were acquired immediately preceding task commencement and every ten minutes thereafter during task performance. Due to normal inter and intra-participant variability of electrophysiologic measures, the following measures of SMNF are presented graphically using relative scaling. Scales are standardized for each measure to facilitate comparative visual analysis between conditions. Results tables presenting absolute data are included in Appendix 6B.

5.2.1 Stimulus Level

Based on general observation, it would appear that the static and high activity participants (Figures 65 and 68) received a lower electrophysiological stimulus voltage than the low and medium activity groups (Figures 66 and 67). Stimulus level effect is explored as a potential confounder in the analysis section. Absolute data are included in Appendix 6B, Table 1.
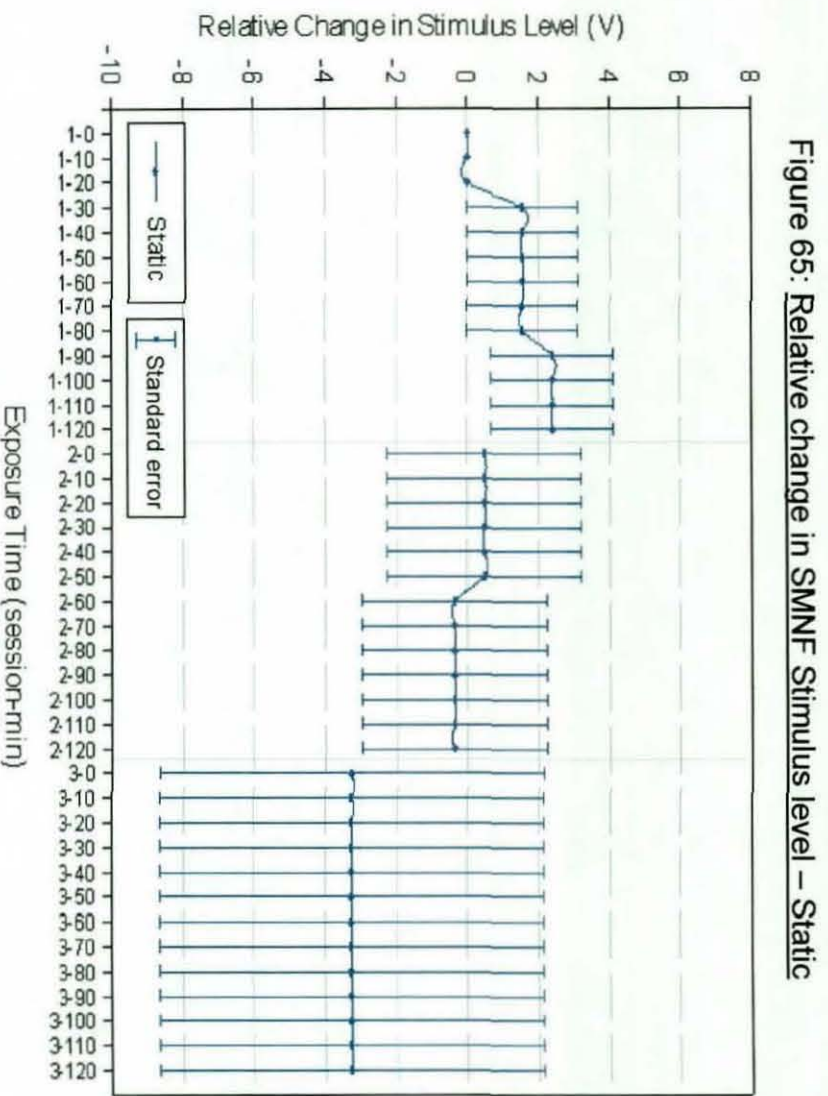
Figure 65: Relative change in SMNF Stimulus level – Static
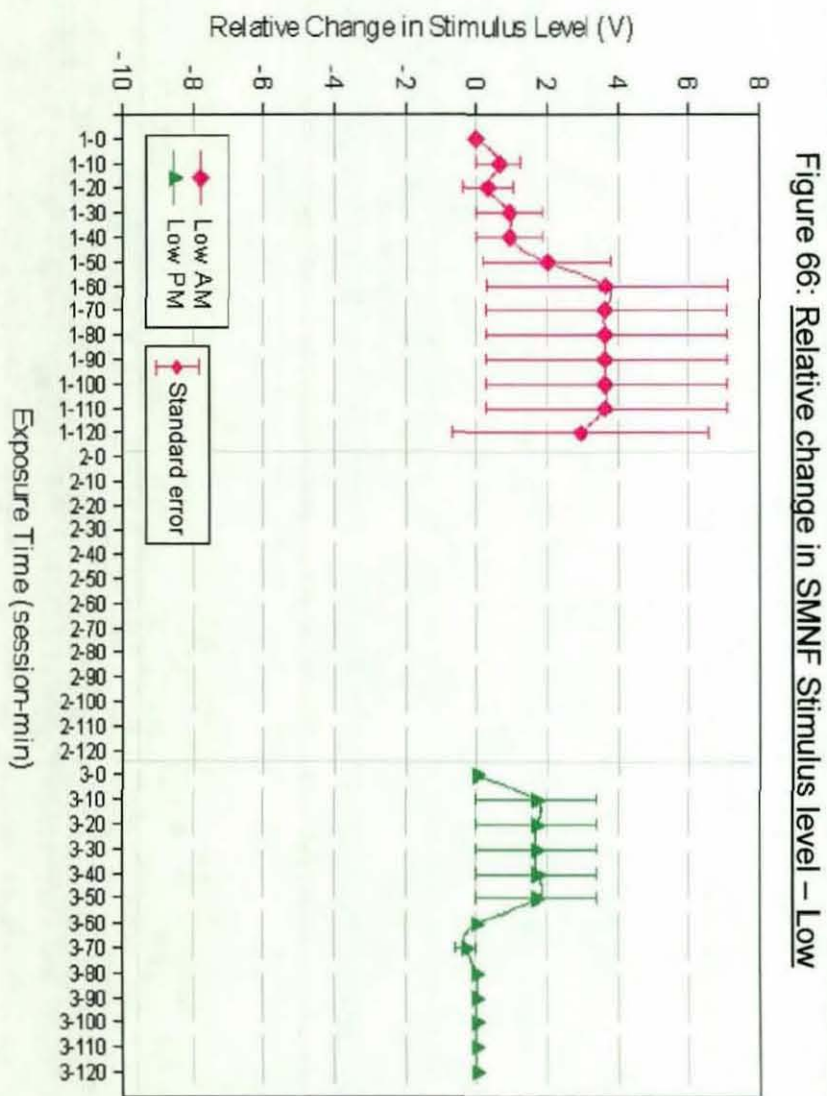
Figure 66: Relative change in SMNF Stimulus level – Low
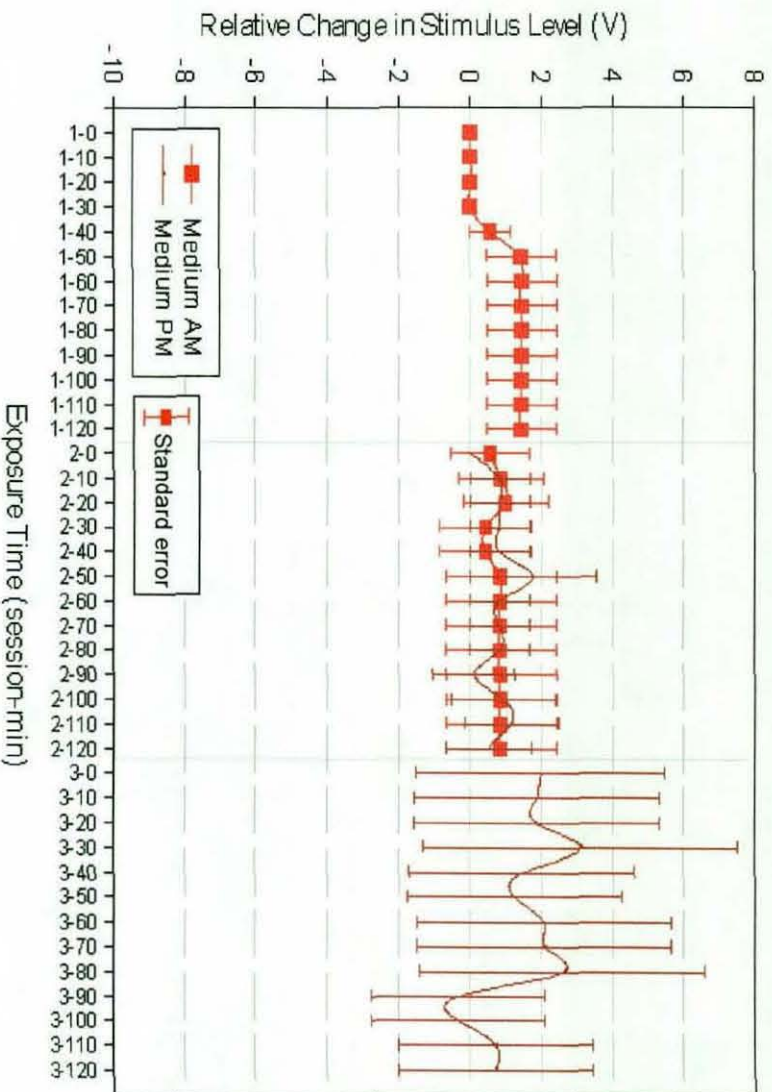
Figure 67: Relative change in SMNF Stimulus level – Medium
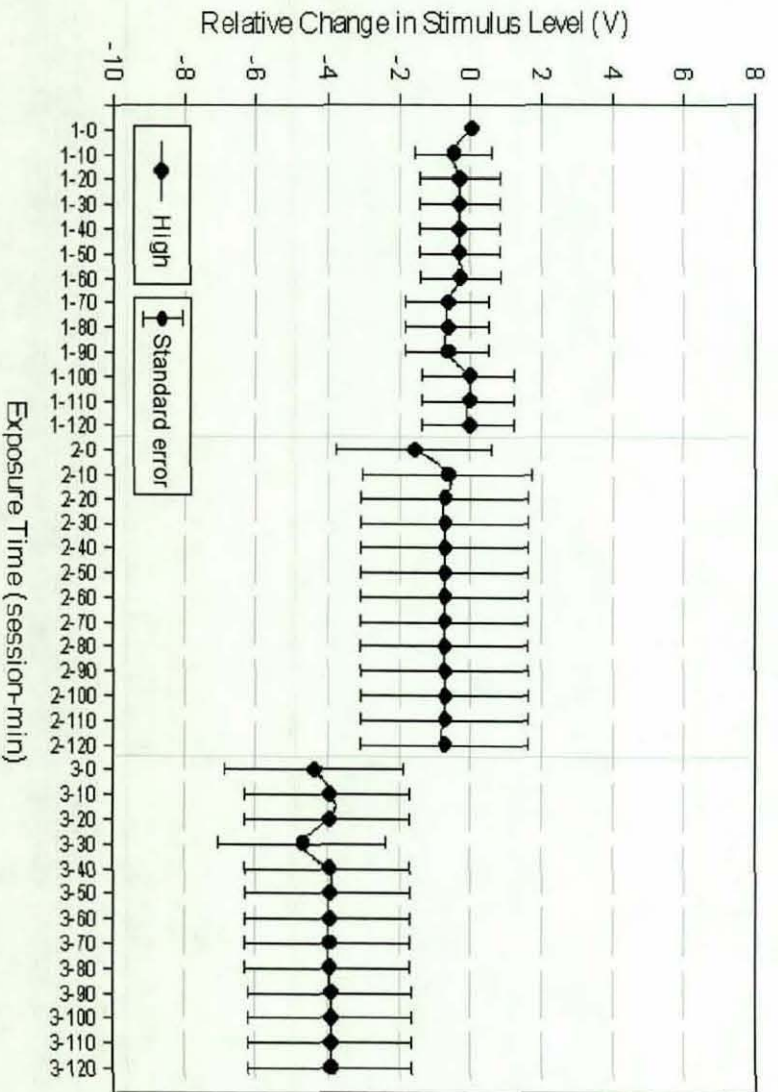
Figure 68: Relative change in SMNF Stimulus level – High

5.2.2 Onset Latency

Onset latency is a measure of the period between stimulus presentation and response of the fastest sensory nerve fibers. A false onset point is sometimes detected due to signal artifact. Hence, software algorithms may miscalculate onset latency. The reliability of onset latency as an objective measure of median nerve function is therefore questionable.

Across conditions, onset latency tended to increase during the first session and decrease during the third session. Little change is noted between endpoints of the second session. Overall, the effect across the workday appears to be negligible (Figures 69-72). Absolute data are presented in Appendix 6B, Table 2.

Figure 69: <u>Relative change in SMNF Onset latency – Static</u>

Exposure Time (session-min)
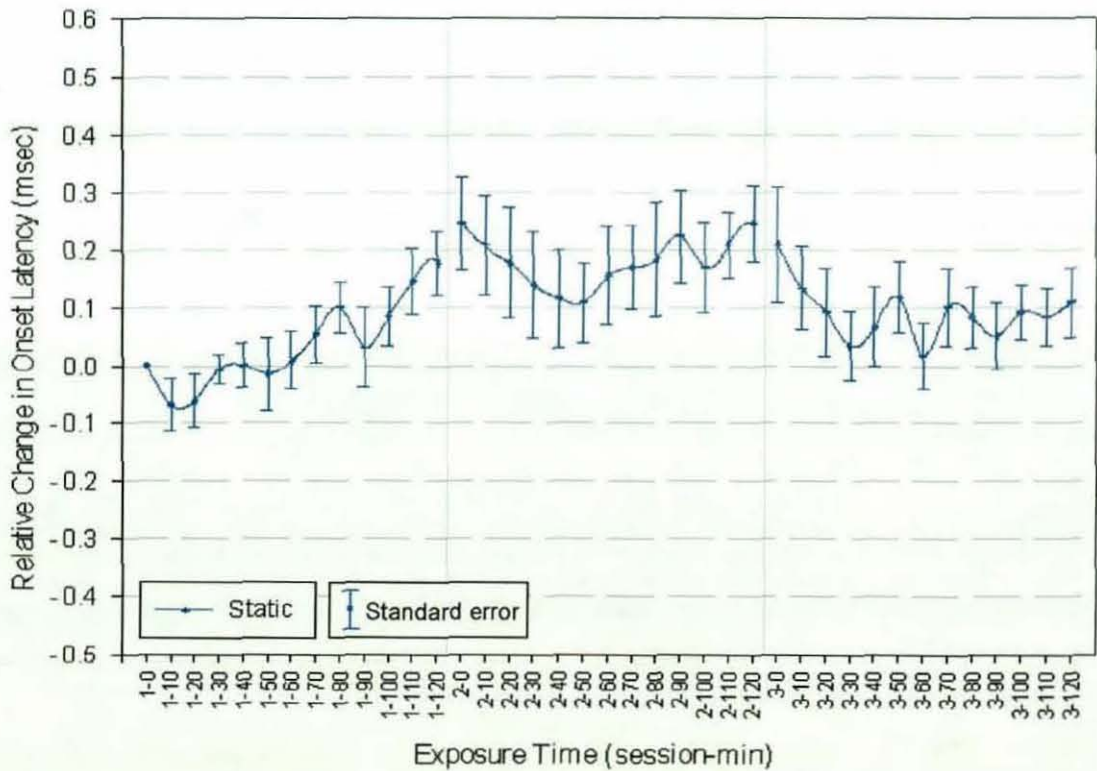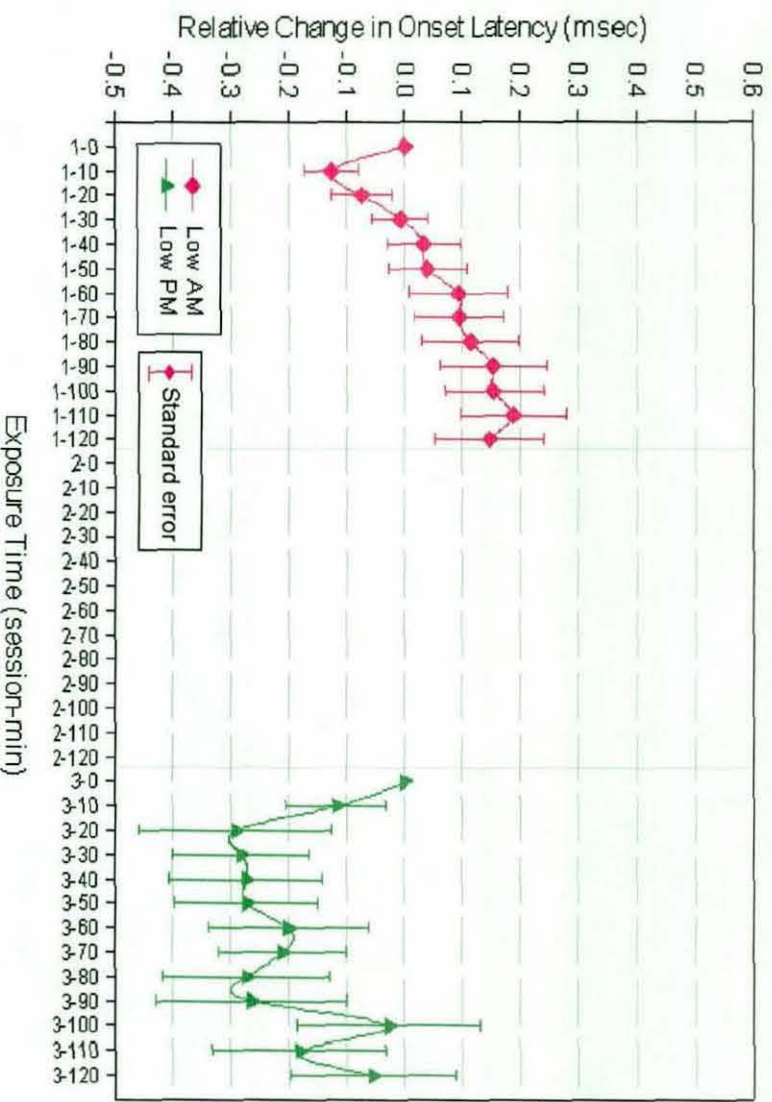
Figure 70: Relative change in SMNF Onset latency – Low
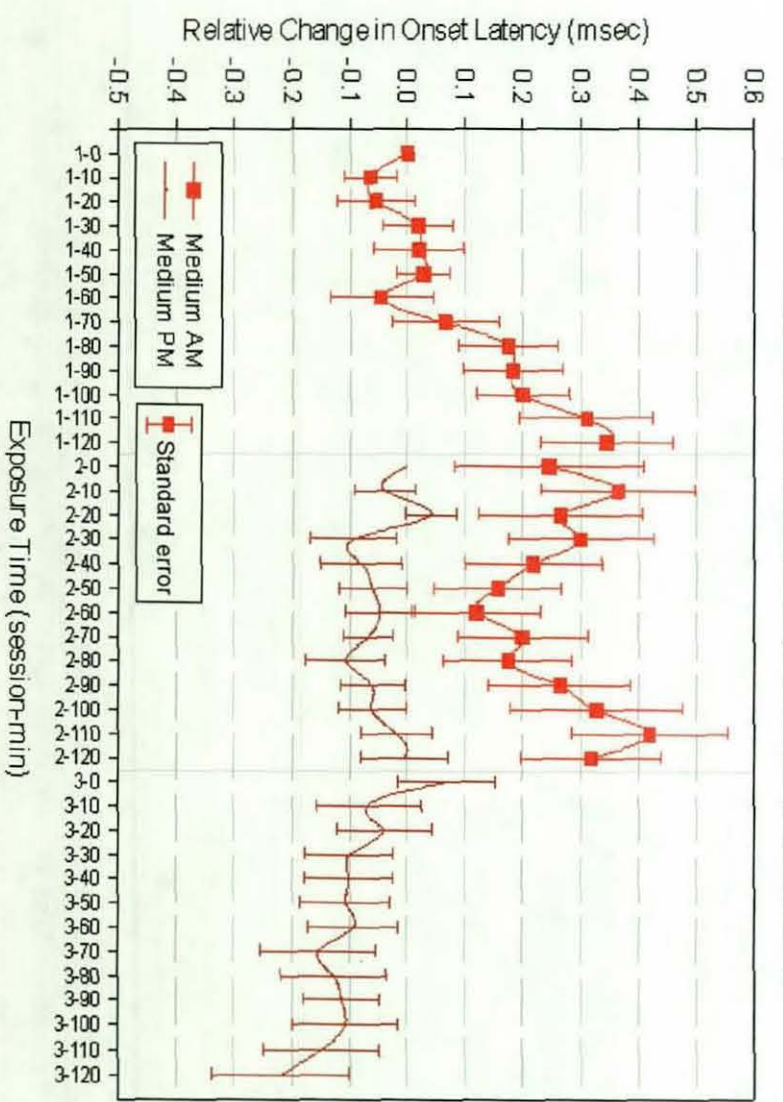
Figure 71: Relative change in SMNF Onset latency – Medium

Figure 72: <u>Relative change in SMNF Onset latency – High</u>
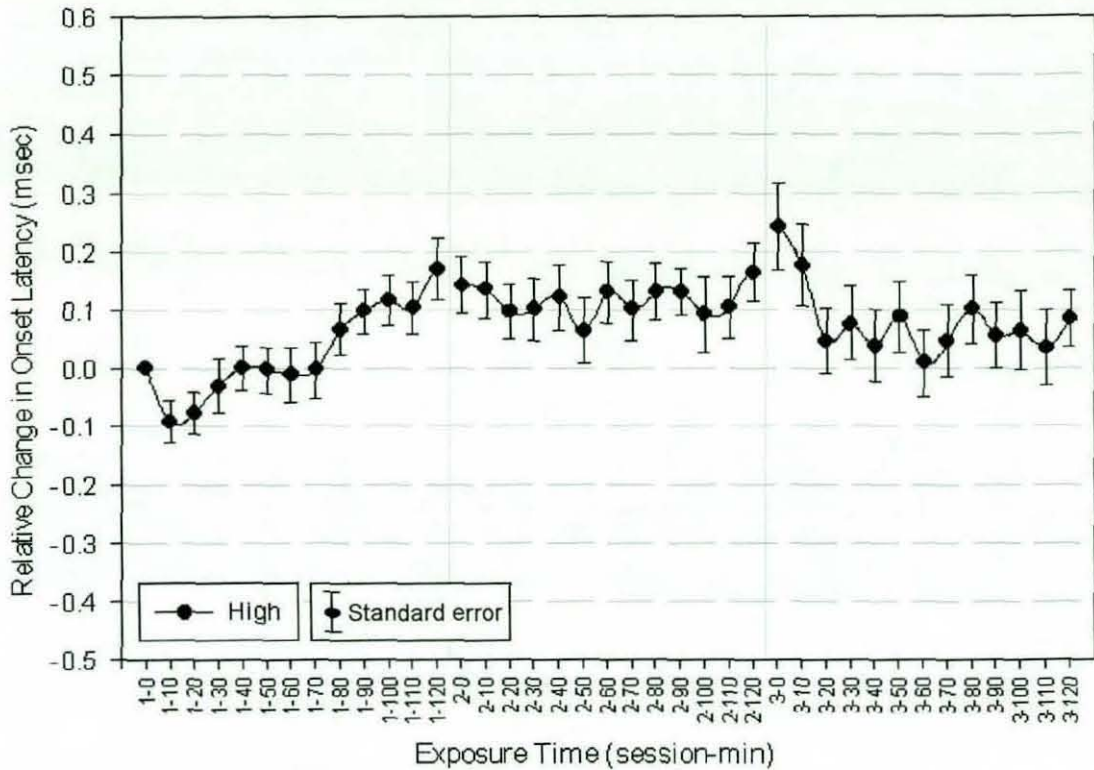
5.2.3 Peak Latency

Peak latency is identifiable within the waveform response to a presented stimulus as the time at which the greatest number of nerve fibers responds. Software algorithms are able to accurately identify this measure with repeatability. Peak latency is considered a reliable objective measure of sensory median nerve function.

Similar to observed findings for measures of onset latency, across conditions peak latency tends to increase during session one, is unchanged between endpoints of session two and decreases during session three. The overall effect across sessions appears to be negligible.

Based on observation, medium wrist activity (Figure 75) appears to produce the greatest effect on peak latency, compared to the static, low and high conditions (Figures 73, 74 and 76). Absolute data are included in Appendix 6B, Table 3.
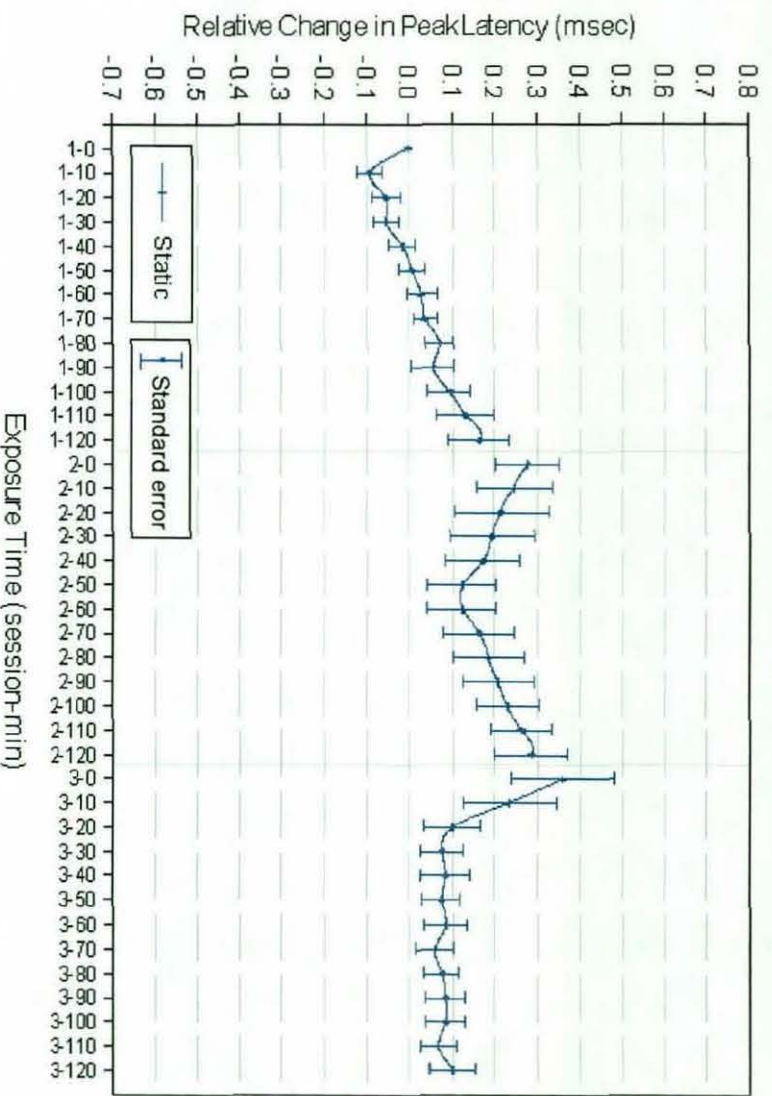
Figure 73: Relative change in SMNF Peak latency – Static
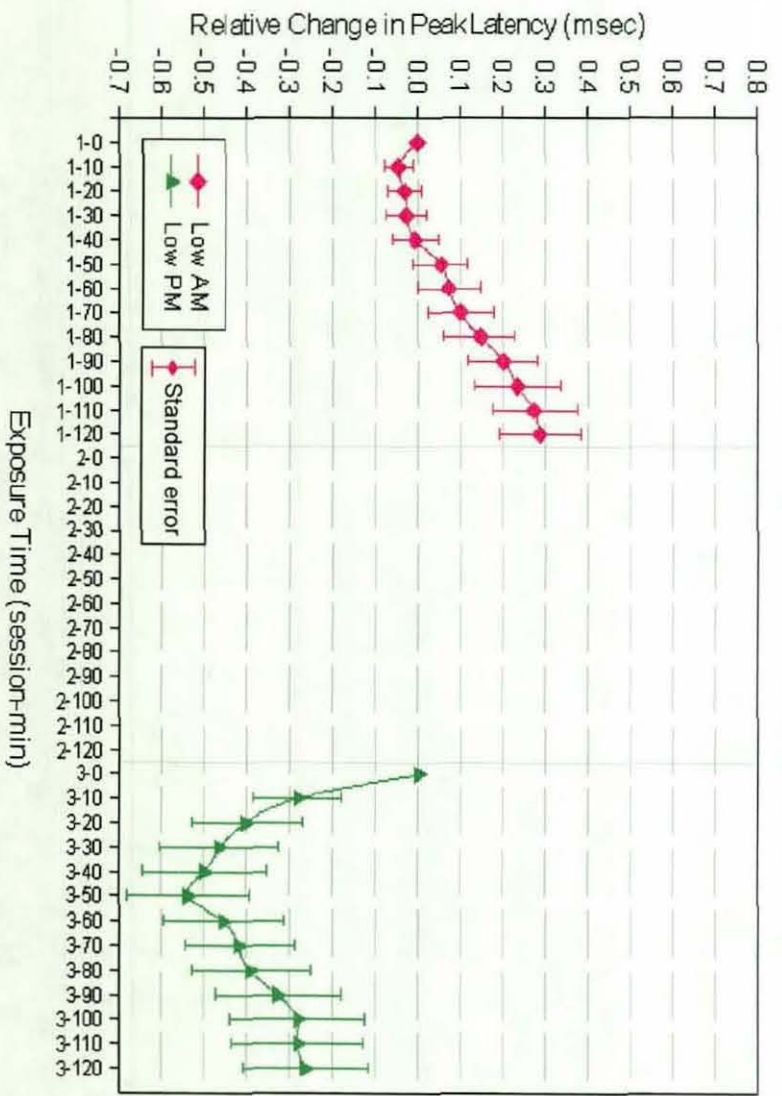
Figure 74: Relative change in SMNF Peak latency – Low
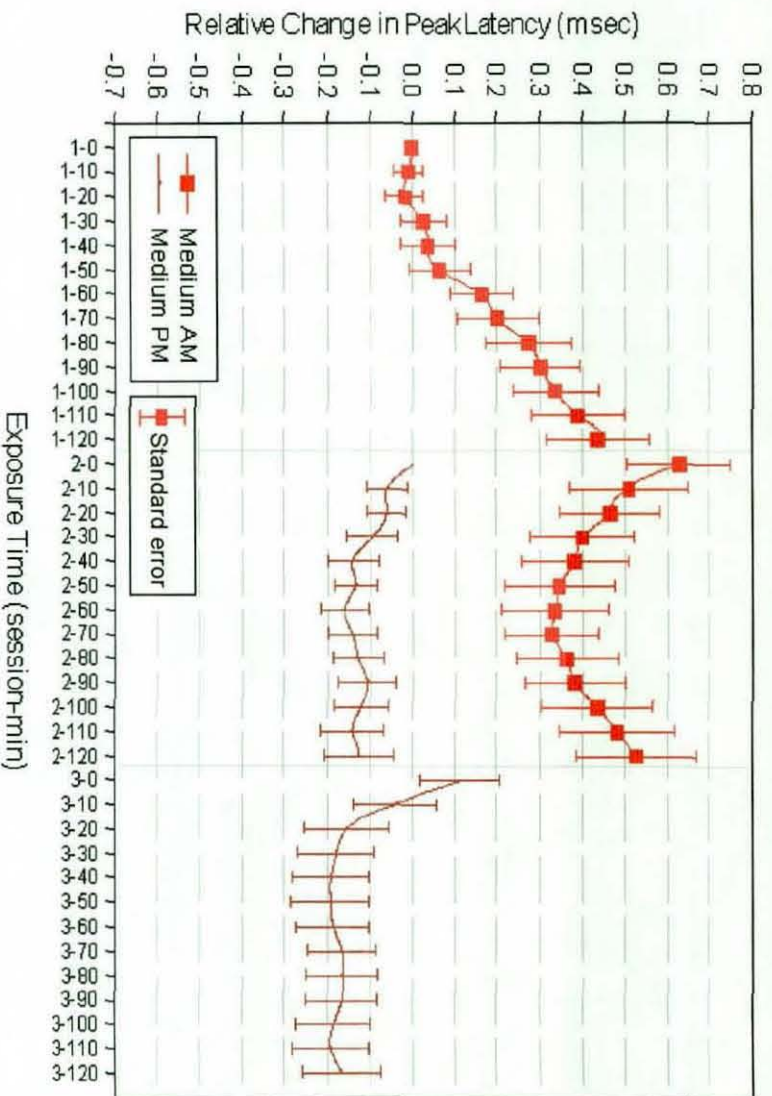
Figure 75: Relative change in SMNF Peak latency – Medium
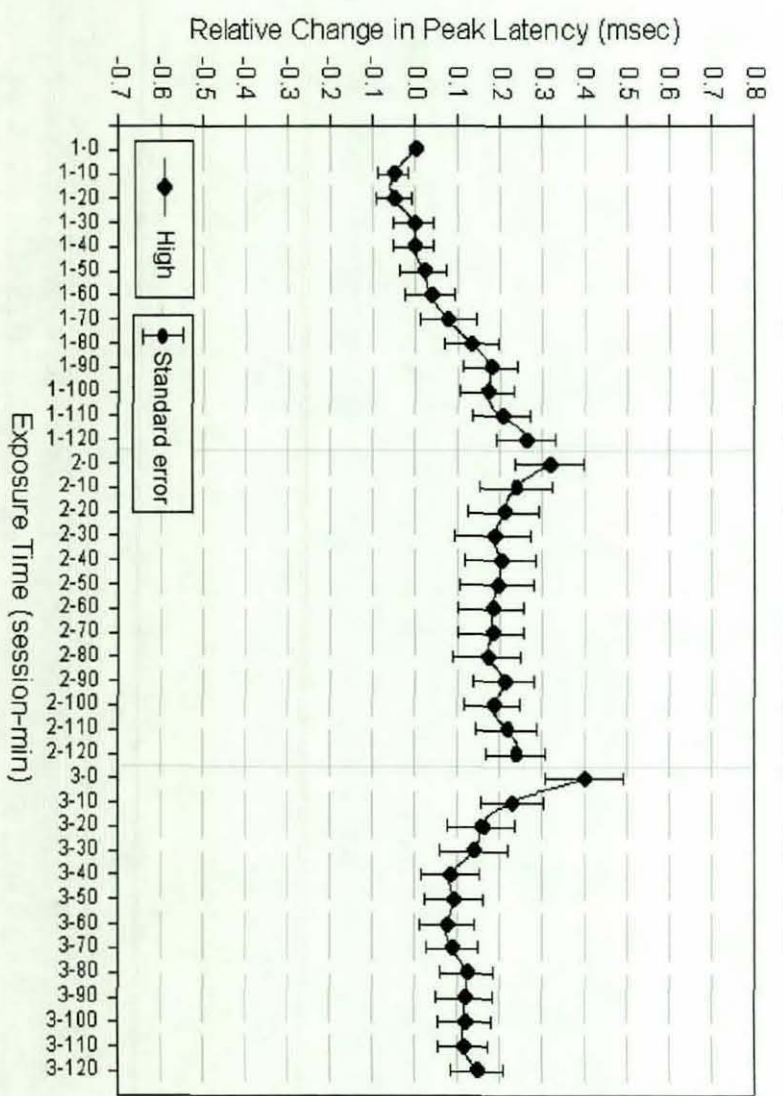
Figure 76: Relative change in SMNF Peak latency – High

5.2.4 Duration

Duration is calculated as the difference in time between onset and peak latency measures. The validity of this derivative measure is compromised by the reliability of its components, specifically onset latency, as discussed earlier.

Based on observations, there appears to be little effect within and between sessions for the static and high wrist activity conditions (Figures 77 and 80, respectively). While a greater effect on duration is seen for the low and medium conditions (Figures 78 and 79), an increase in standard error of measures is also noted. Absolute data are presented in Appendix 6B, Table 4.

Figure 77: <u>Relative change in SMNF Duration – Static</u>

Exposure Time (session-min)
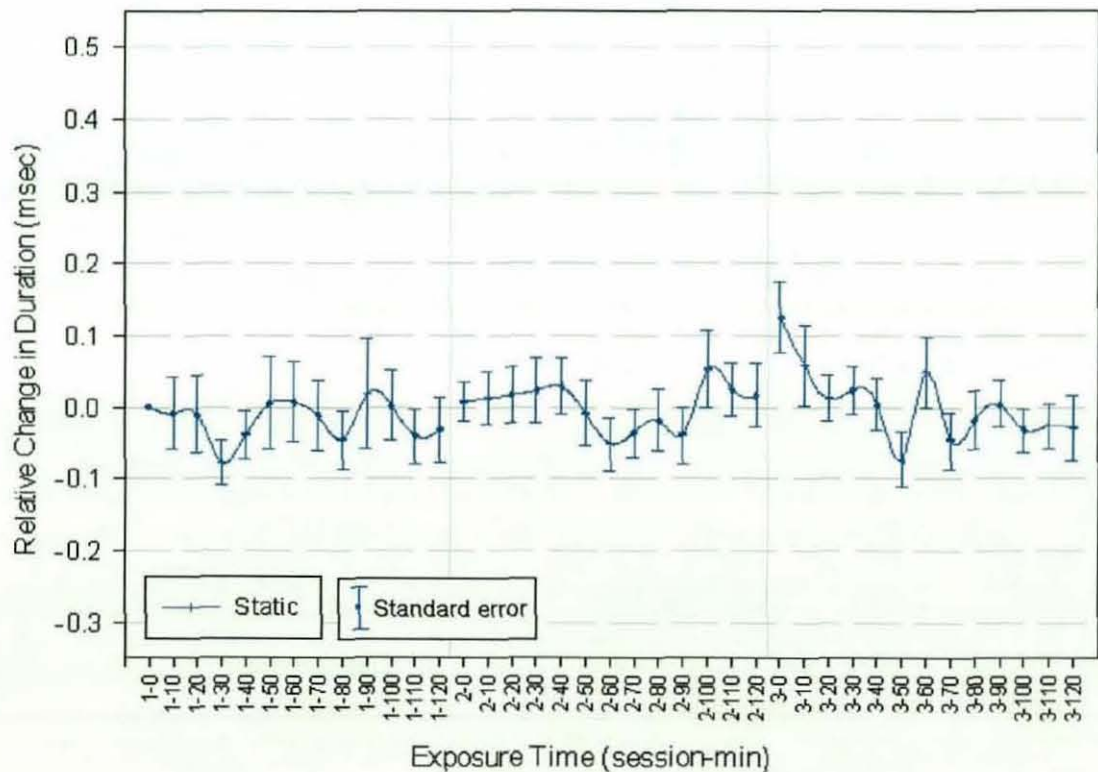
Figure 78: Relative change in SMNF Duration – Low
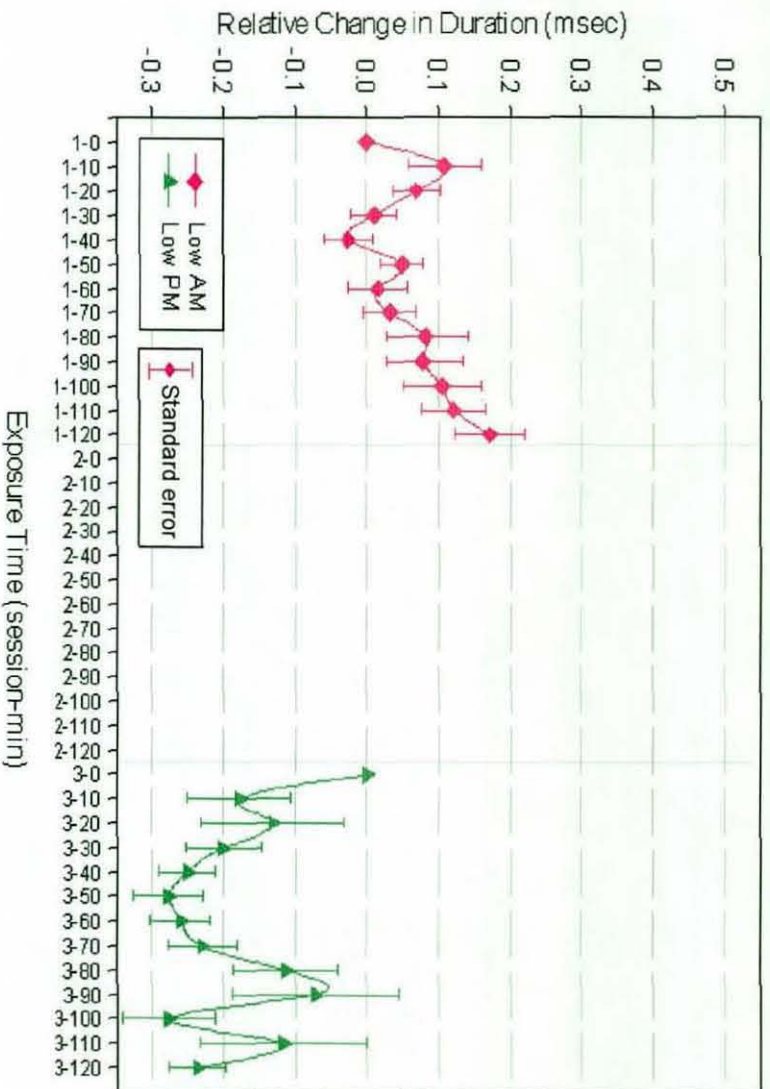
Figure 79: Relative change in SMNF Duration – Medium
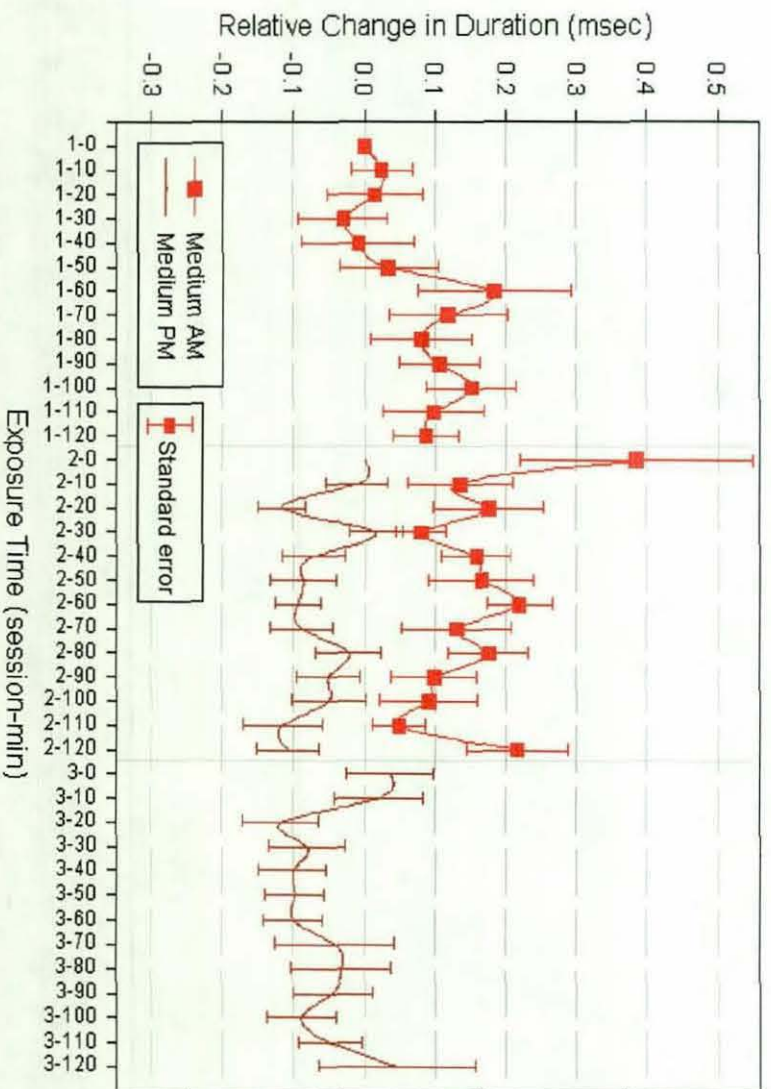
Figure 80: <u>Relative change in SMNF Duration – High</u>

Exposure Time (session-min)
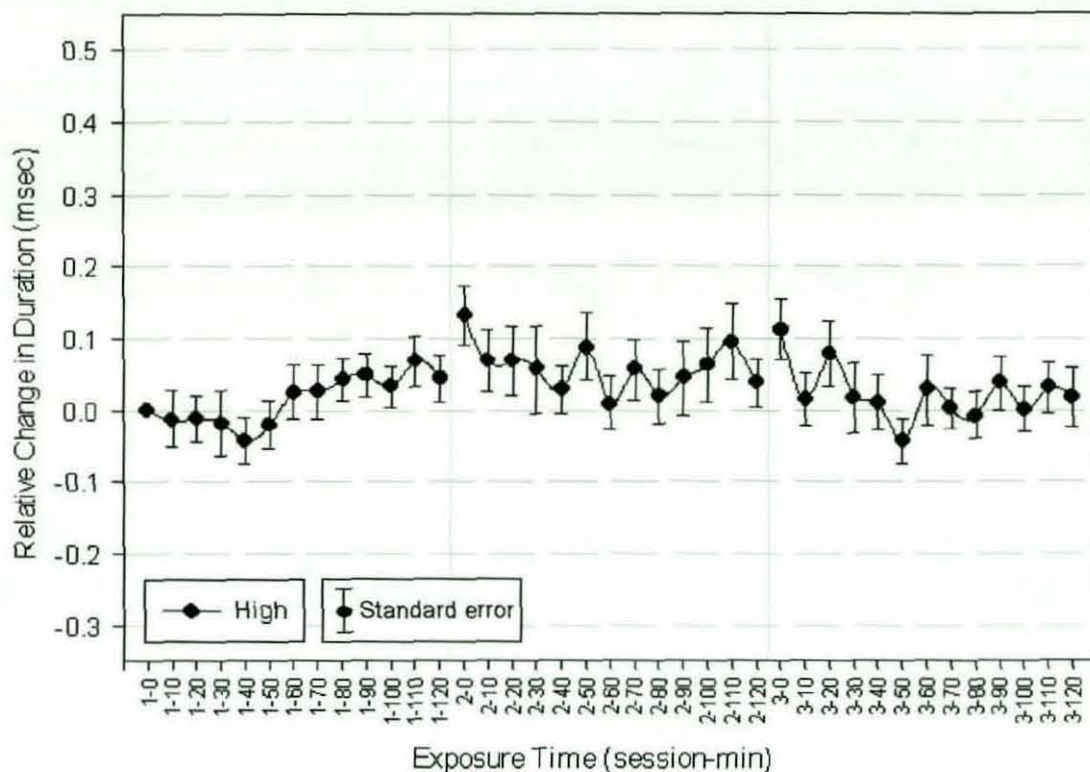
5.2.5 Amplitude

Amplitude is the measure of peak magnitude of responding nerve fibers. This measure may be influenced by several external as well as internal variables, including electrode placement, skin conductivity, sweating, and stimulus level. Although confounding variables were controlled to the extent possible, amplitude remains an unreliable measure of sensory median nerve function.

High standard error of measures is suggestive that a true effect of wrist activity on SMNF amplitude may be difficult to identify (Figures 81-84). Absolute data are included in Appendix 6B, Table 5.

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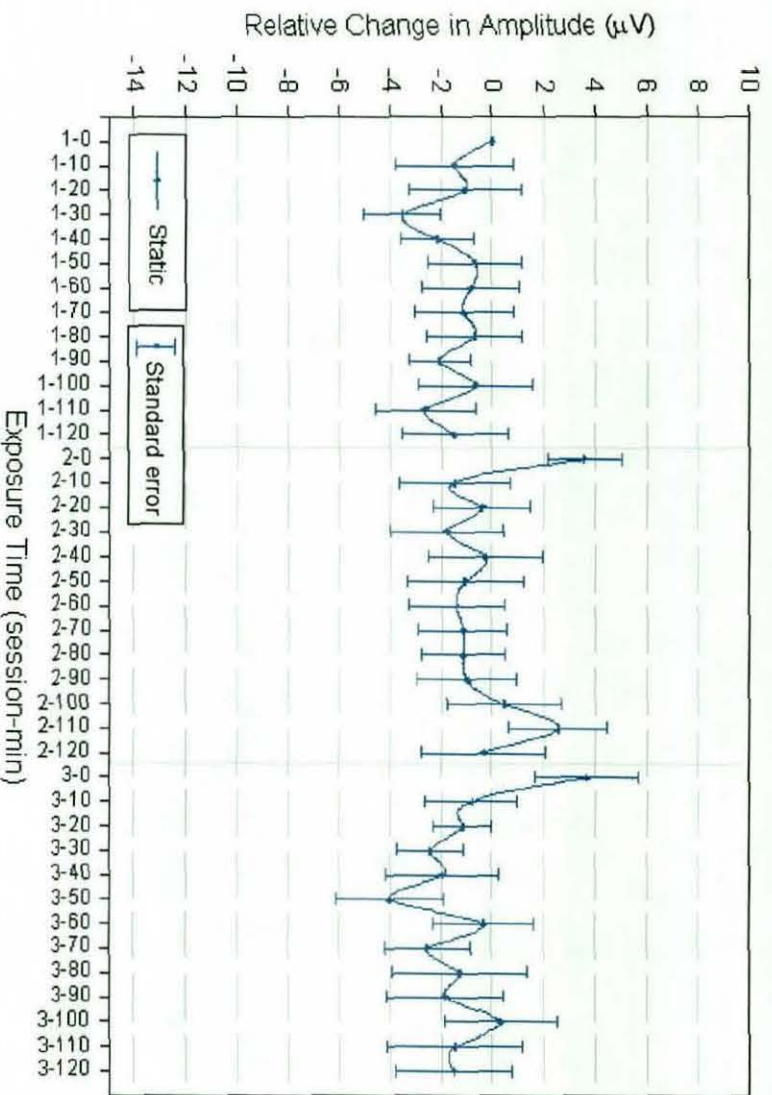
Figure 81: Relative change in SMNF Amplitude – Static
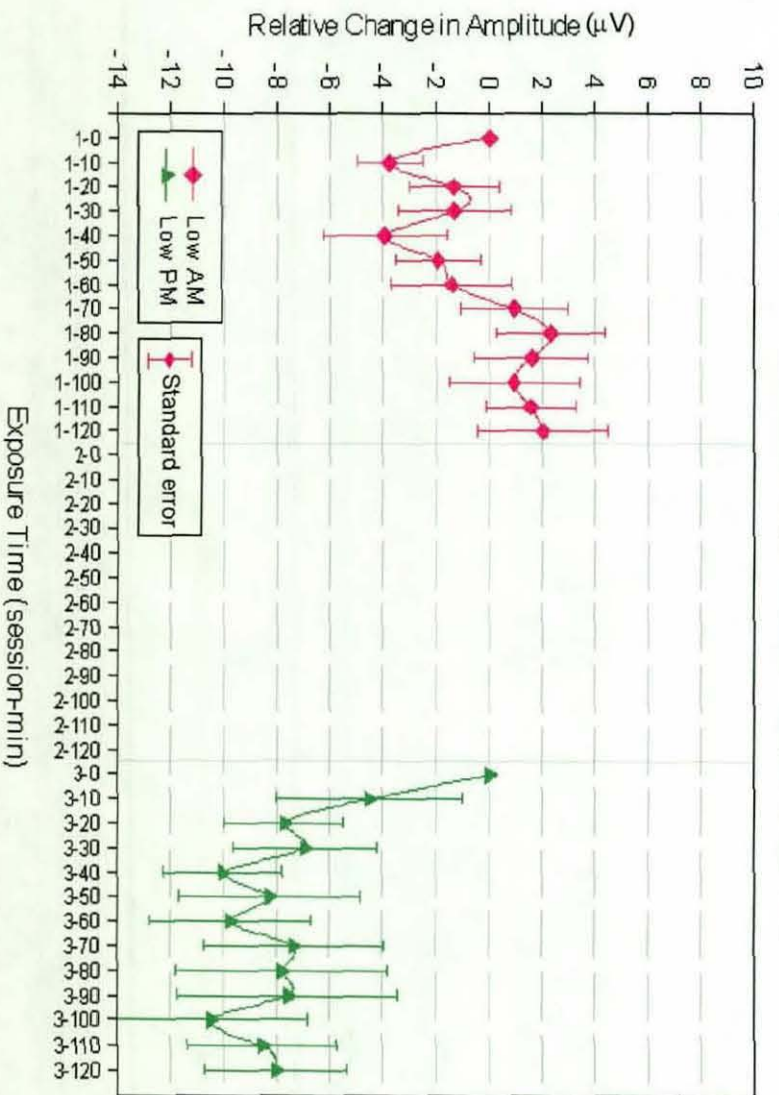
Figure 82: Relative change in SMNF Amplitude – Low

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Figure 84: Relative change in SMNF Amplitude – High

Figure 83: Relative change in SMNF Amplitude – Medium

5.2.6 Area

Area under the waveform is calculated as a function of base length (duration) and height (amplitude). Since both duration and amplitude measures may be influenced by confounding factors and are therefore unreliable measures, the derivative measure of area will likely also present an unreliable definition of sensory median nerve function.

A high standard error of measures is noted, particularly in the third session for low-PM and medium-PM wrist activity conditions (Figures 85-88). Absolute data are presented in Appendix 6B, Table 6.

Figure 85: <u>Relative change in SMNF Area – Static</u>

Exposure Time (session-min)
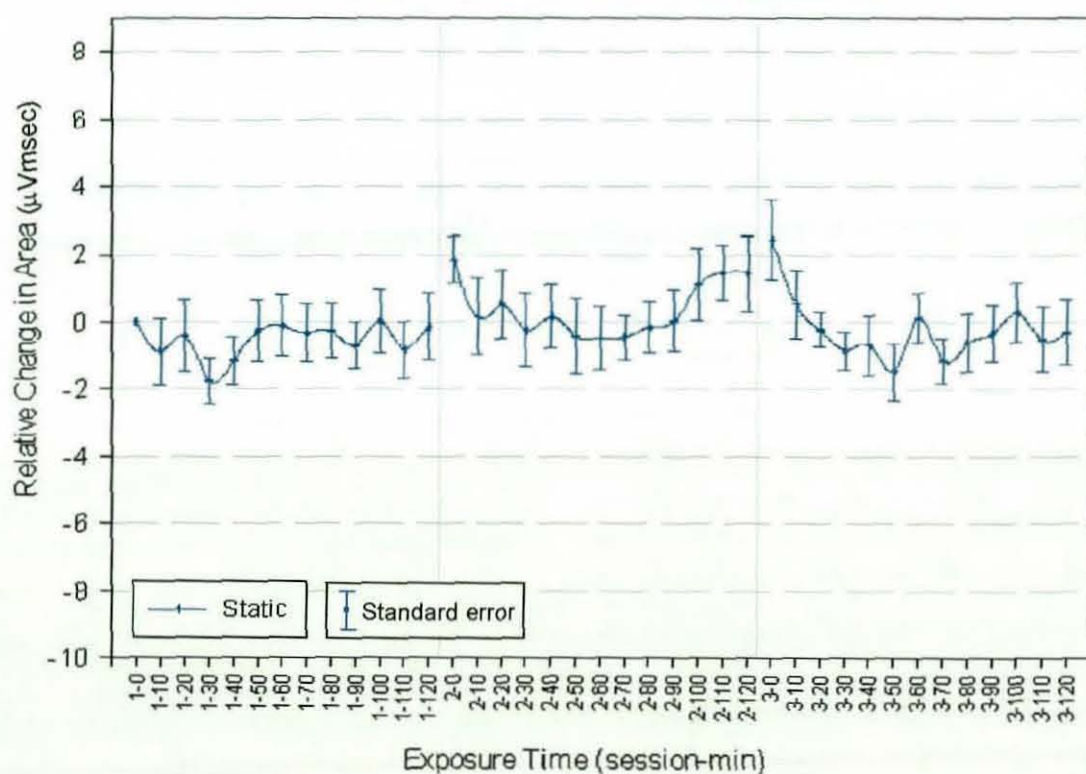
Figure 86: Relative change in SMNF Area – Low
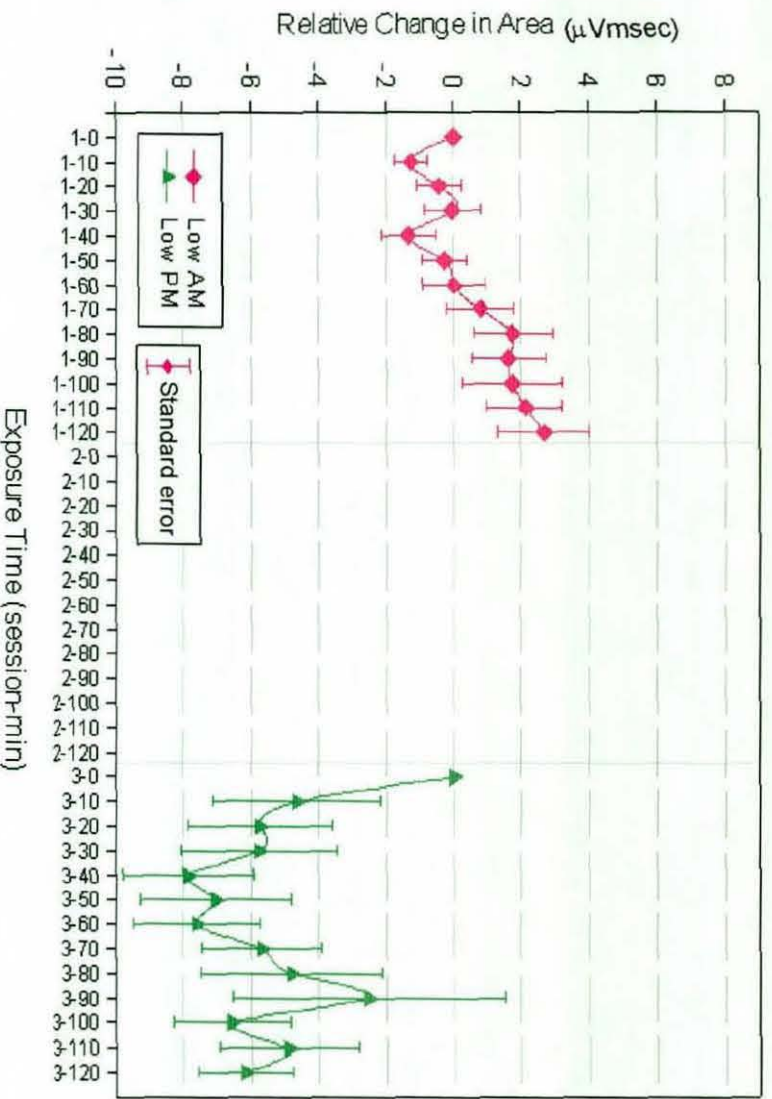
Figure 87: Relative change in SMNF Area – Medium
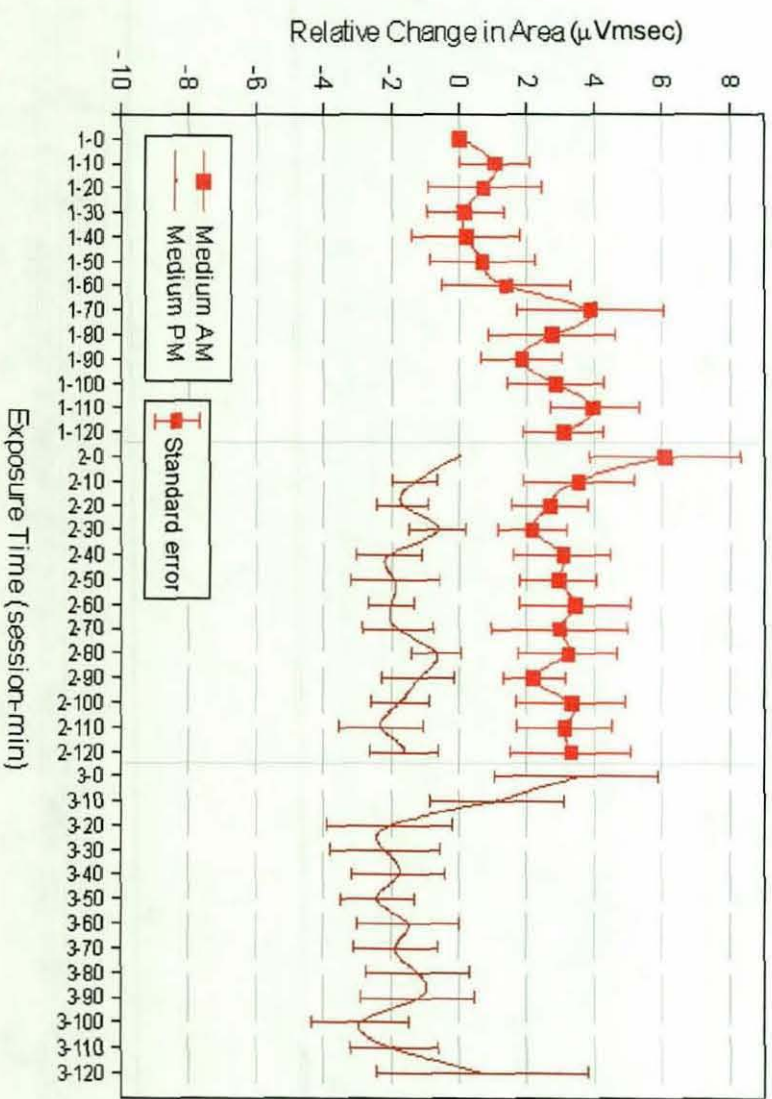
Figure 88: <u>Relative change in SMNF Area – High</u>
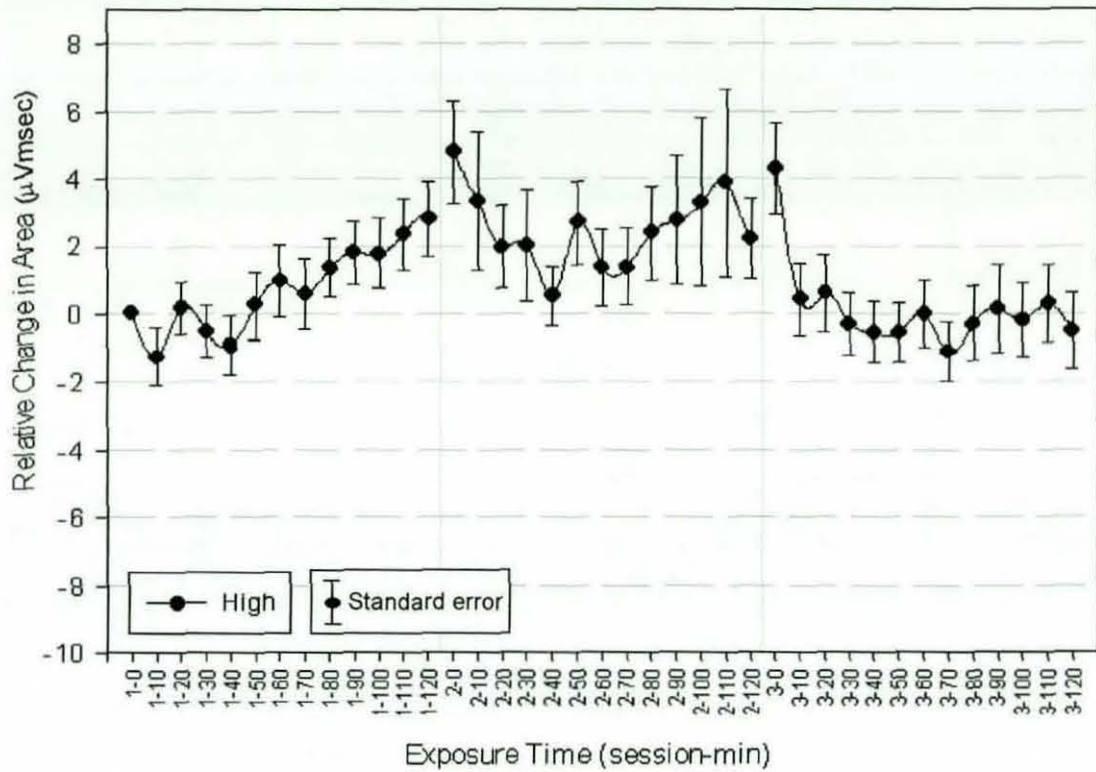
5.2.7 Conduction Velocity

Anatomical landmarks were used for stimulus and recording electrode placement. Stimulated nerve length thus varied between participants as a function of hand length. Sensory nerve conduction velocity (SNCV), computed as peak latency divided by stimulated nerve length is a distance corrected value of peak latency.

Across conditions, SNCV tended to decrease during the first session, was relatively unchanged between endpoints of the second session and recovered during the third session. The overall effect across workday sessions appears to be negligible.

Effects within and between sessions appear to be similar between conditions (Figures 89-92). Absolute data are included in Appendix 6B, Table 7.
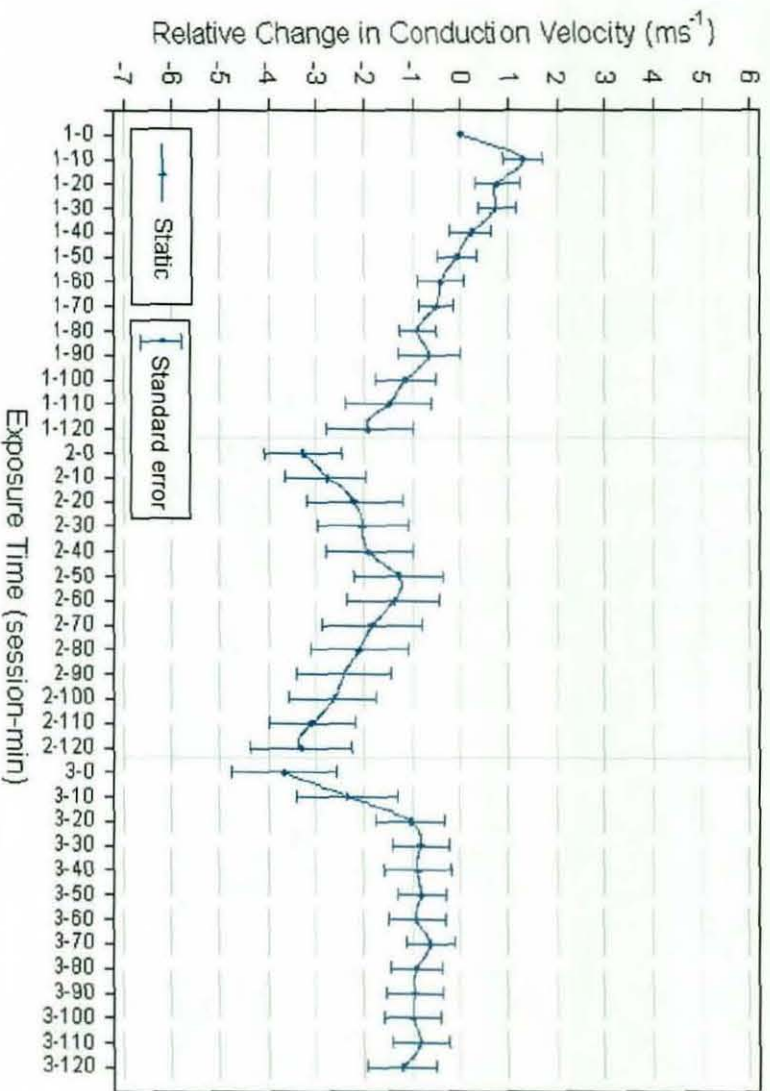
Figure 89: Relative change in SMNF Conduction velocity – Static
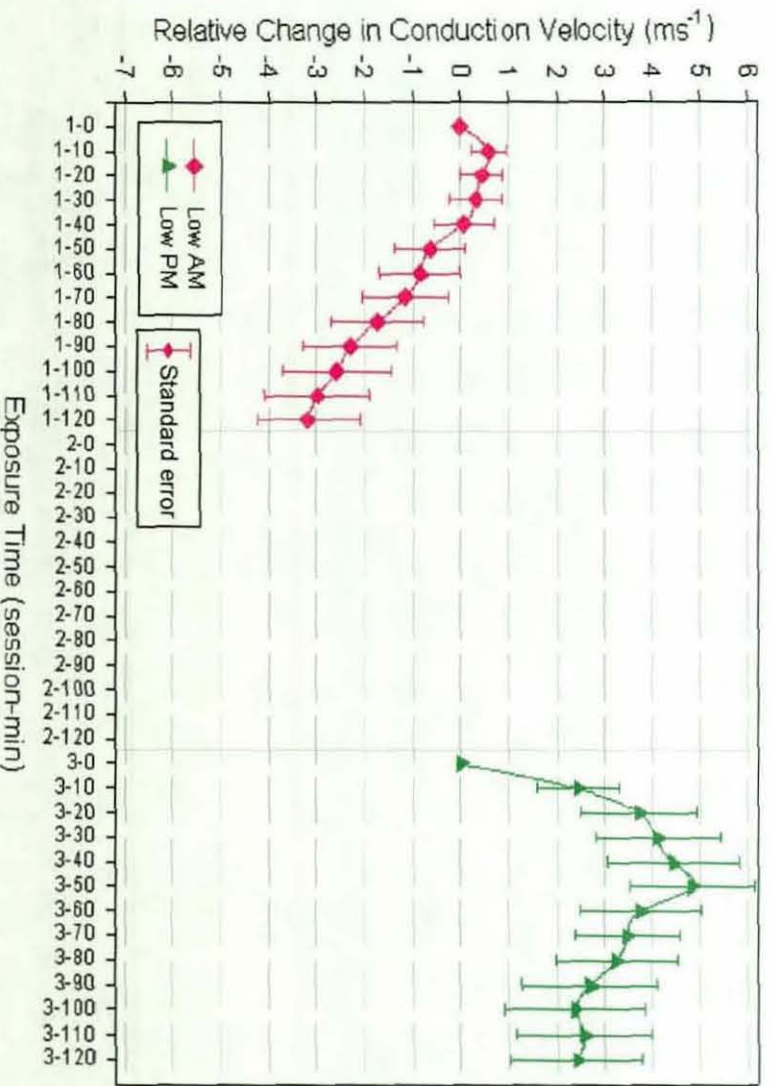
Figure 90: Relative change in SMNF Conduction velocity – Low
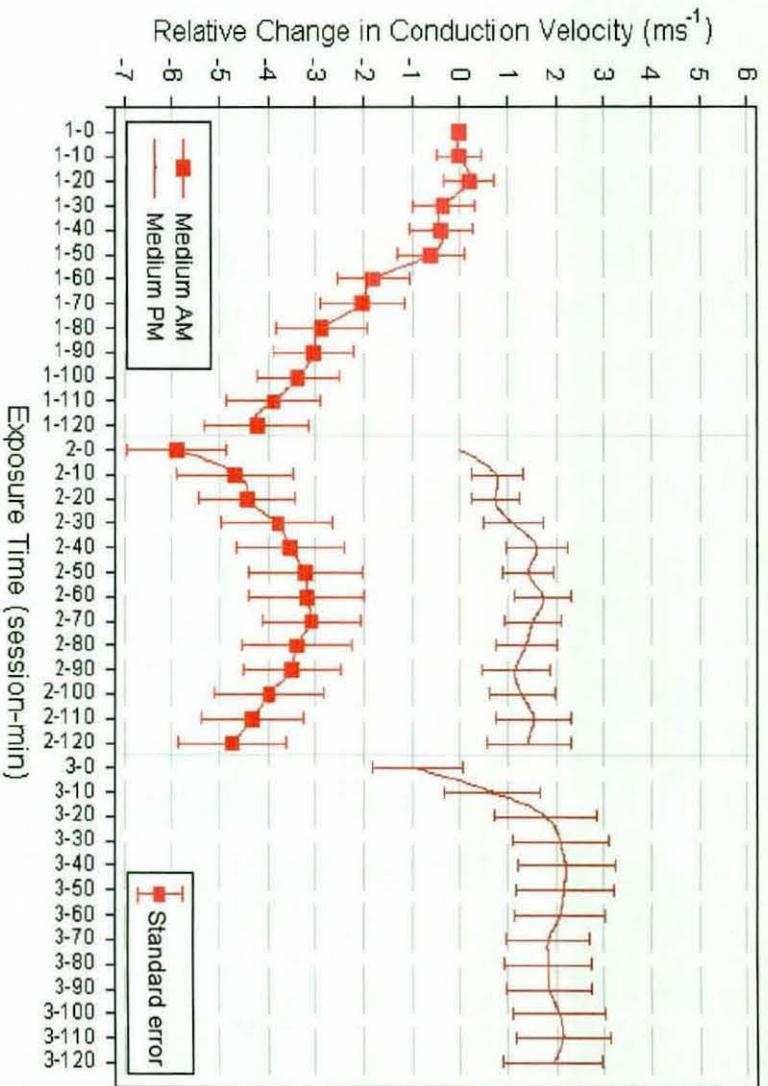
Figure 91: Relative change in SMNF Conduction velocity – Medium
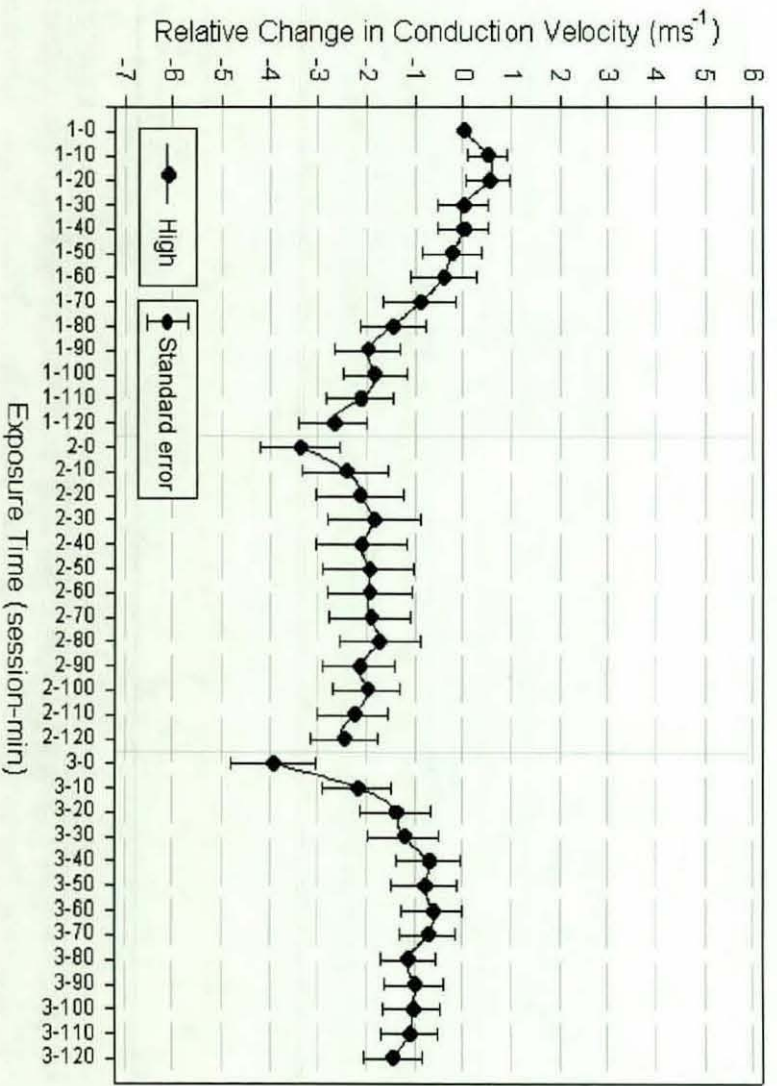
Figure 92: Relative change in SMNF Conduction velocity – High

5.3 Subjective Comfort

Perceived subjective comfort was solicited immediately preceding task commencement and at the conclusion of each hour of task performance using a standardized questionnaire instrument (Appendix 1C).

Approximately one half of all participants professed symptoms that were suggestive of carpal tunnel syndrome, specifically perception of coldness, tingling and/or numbness in the median distribution of the dominant hand. A modified 11-point Borg scale was used to rate the participants perception of dominant hand comfort. Results were calculated across participants for each condition (Appendix 6C).

Results are presented graphically, by condition, using relative scaling (Figures 93-96). A decrease in subjective comfort for the low, medium and high wrist activity conditions is noted during the course of the workday. Across sessions a slight improvement in perceived comfort is indicated for the static group. The sensitivity of subjective comfort rating as a measure of exposure to physical stressors will be explored in the analysis chapter.

Figure 93: Relative change in subjective comfort rating – Static
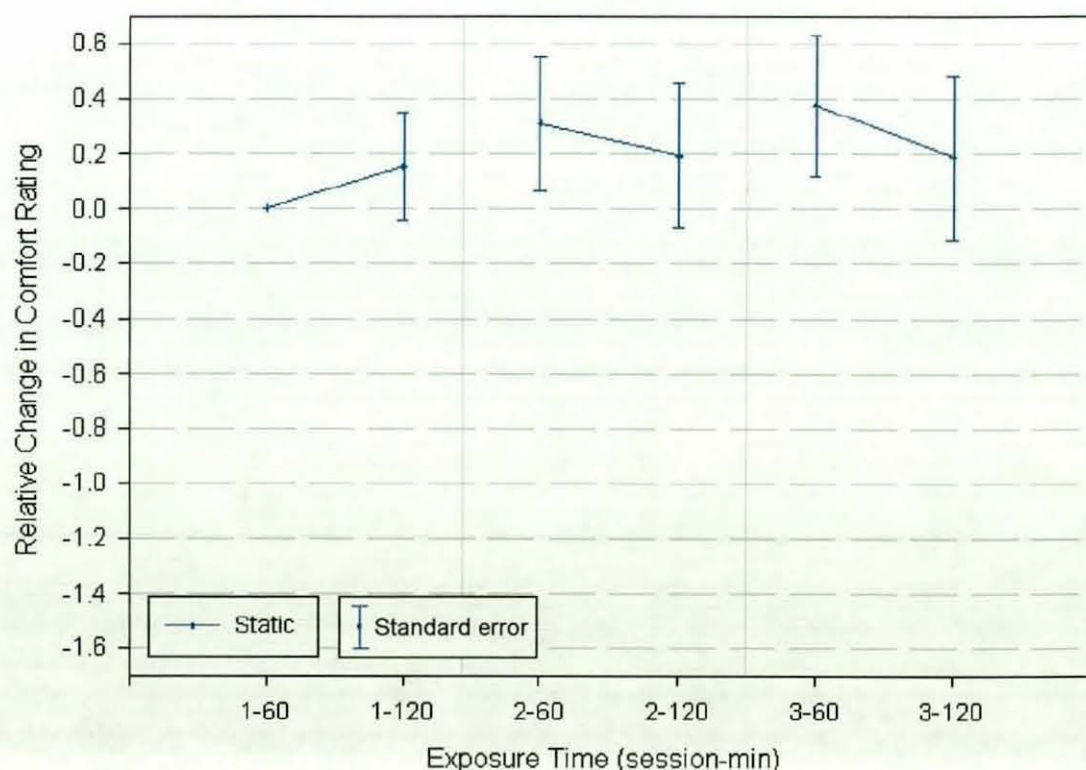
Figure 94: <u>Relative change in subjective comfort rating – Low</u>
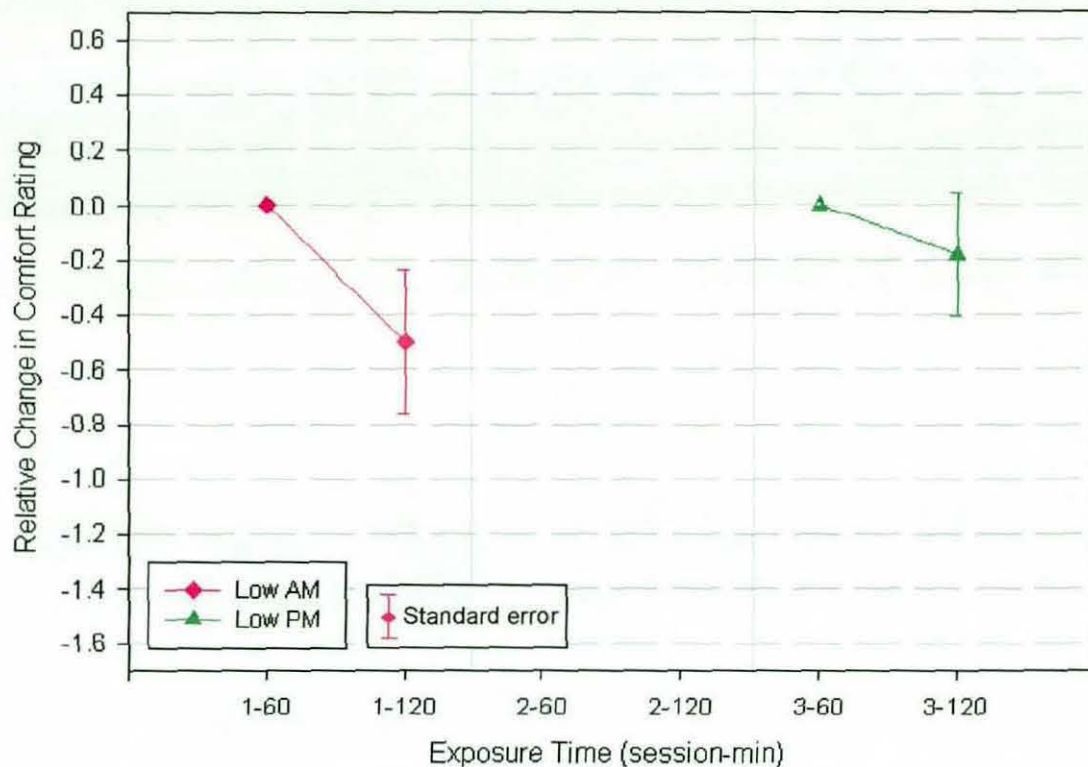
Figure 95: <u>Relative change in subjective comfort rating – Medium</u>
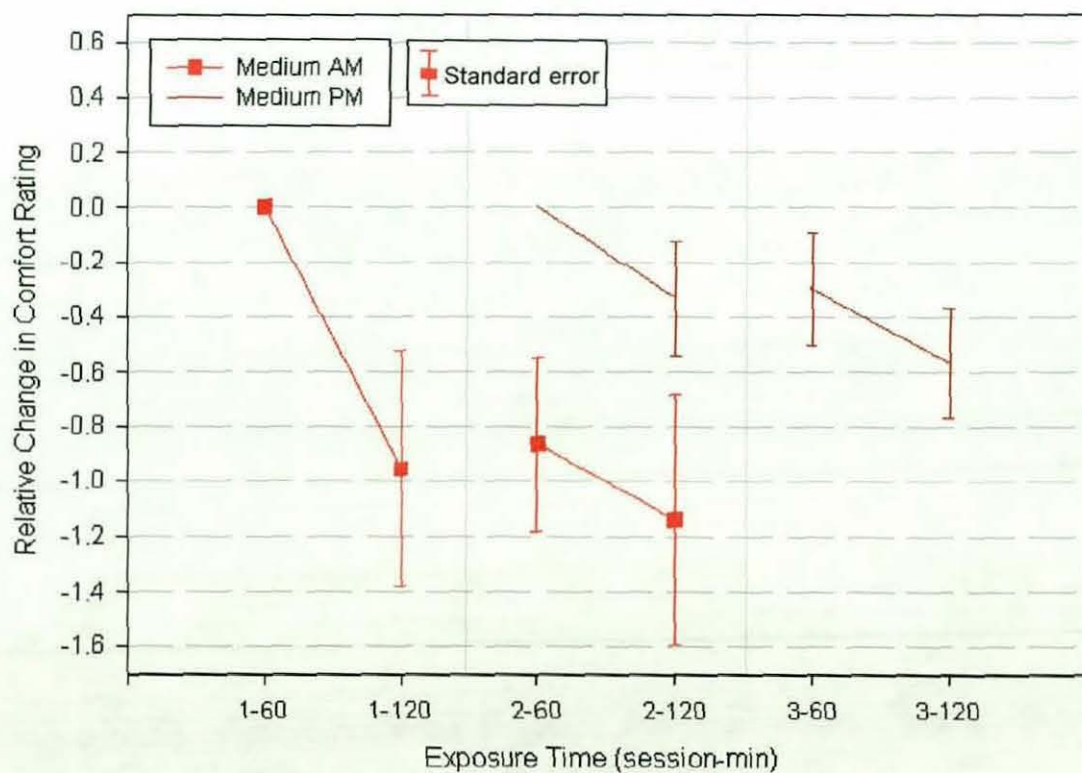
Figure 96: <u>Relative change in subjective comfort rating – High</u>
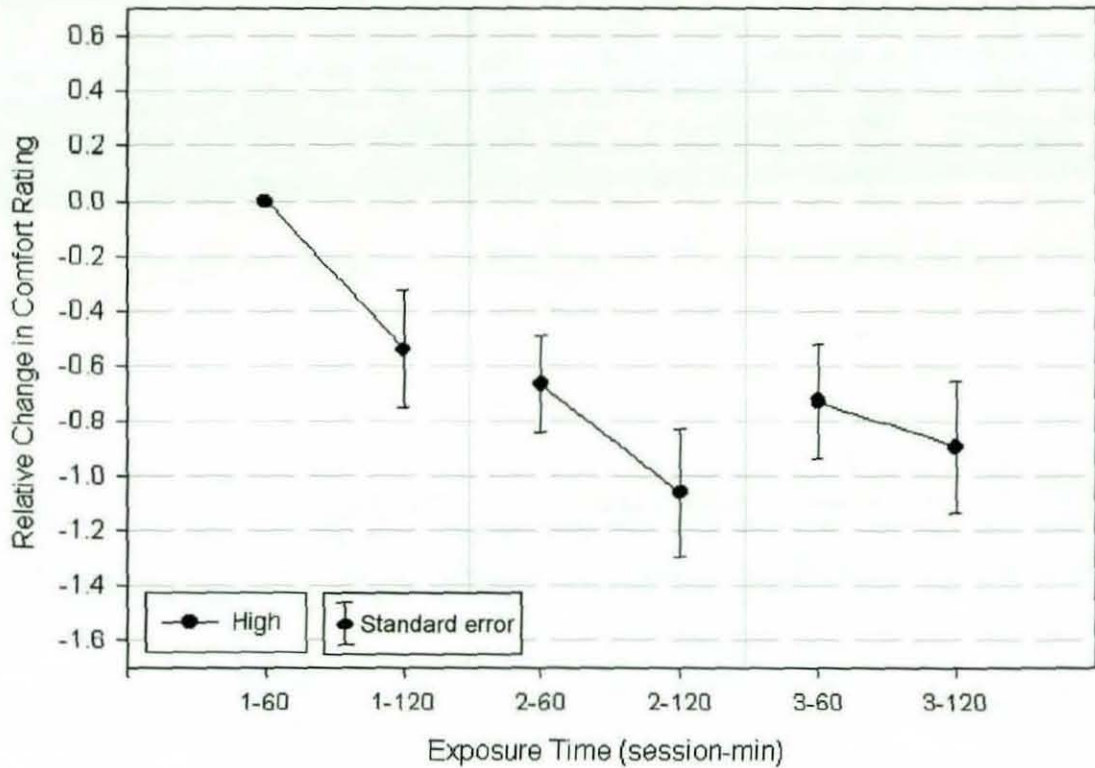
5.4 Room Temperature

Results for room temperature were calculated across participants for each condition. Absolute data are presented in Appendix 6D.

Across participants, sessions and conditions, room temperature appears to be very stable (Figure 97), suggesting that environmental controls implemented throughout this study were effective. The potential covariate effect of room temperature on sensory median nerve function will be explored fully in the analysis section.

Figure 97: <u>Absolute room temperature – All conditions</u>
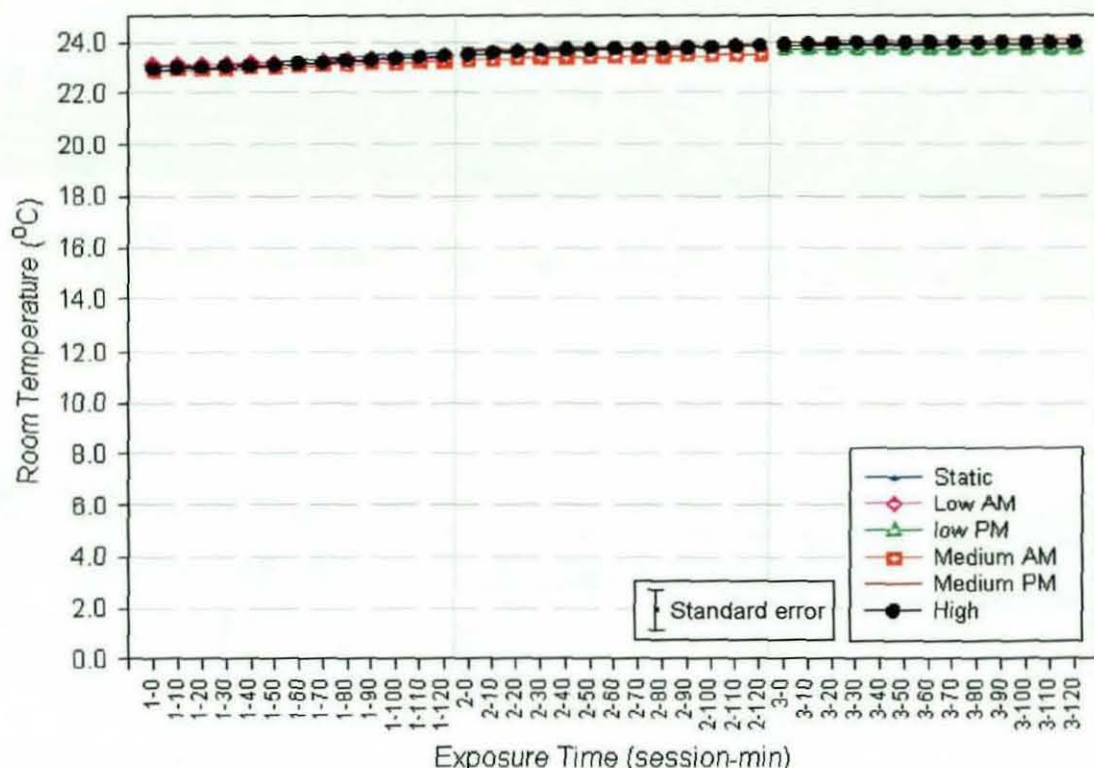
5.5 Near-Nerve Skin Temperature

Near-nerve skin temperature (NNST) was monitored immediately preceding task commencement and every twenty minutes thereafter throughout task performance. Three anatomical reference points along the median nerve were utilized as NNST recording sites: wrist (30mm proximal to the distal wrist crease), hand (over the palmar wrist crease) and fingertip (distal phalanx of the third digit). Results of near-nerve skin temperature were calculated across participants for each condition. Absolute data are presented in Appendix 6E.

In all cases, environmental conditions were monitored and carefully controlled. Mean initial near-nerve skin temperature across participants was similar across conditions at each of the measurement sites.

Exposure to wrist activity corresponding with low, medium and high activity produced a noticeable difference in skin temperature compared with the static condition. Furthermore, the effect on near-nerve skin temperature

appears to be dependent on the magnitude and duration of exposure. This is particularly evident during the first session at the more distal measurement sites.

The general pattern of the skin temperature graphs is similar to that of sensory median conduction velocity, suggesting a possible correlation between measures. The strength of association becomes clearer at the distal temperature monitoring sites. Near-nerve skin temperature measured at the fingertip (distal-most recording site) would appear to present the strongest association with SNCV.

The above observations are highly suggestive of a possible association between thermoregulation of the hand and sensory median nerve performance. Evidence in the literature pertaining to ischemic involvement in the aetiology of carpal tunnel syndrome supports these observations.

5.5.1 Wrist Temperature

Near-nerve skin temperature at the wrist tends to decrease during the first session, is relatively unchanged between endpoints of the second session and increases during the third session. The effect is apparently negatively pronounced for the static condition (Figure 98), is stable for the low condition (Figure 99) and positively pronounced for the medium and high wrist activity conditions (Figures 100 and 101). These observations are suggestive that increased wrist activity promotes blood circulation throughout the hand, the benefits of which seem to exceed any cooling effects of air velocity over the surface area of the hand. Absolute data are included in Appendix 6E, Table 1.
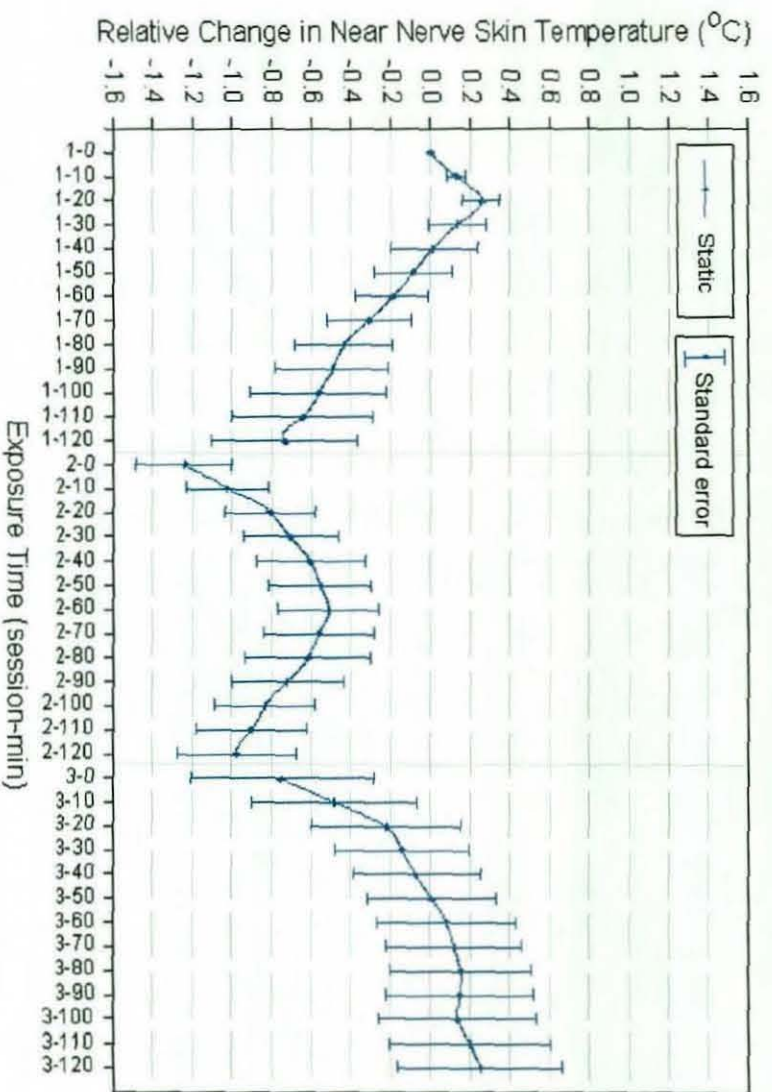
Figure 98: Relative change in wrist temperature – Static
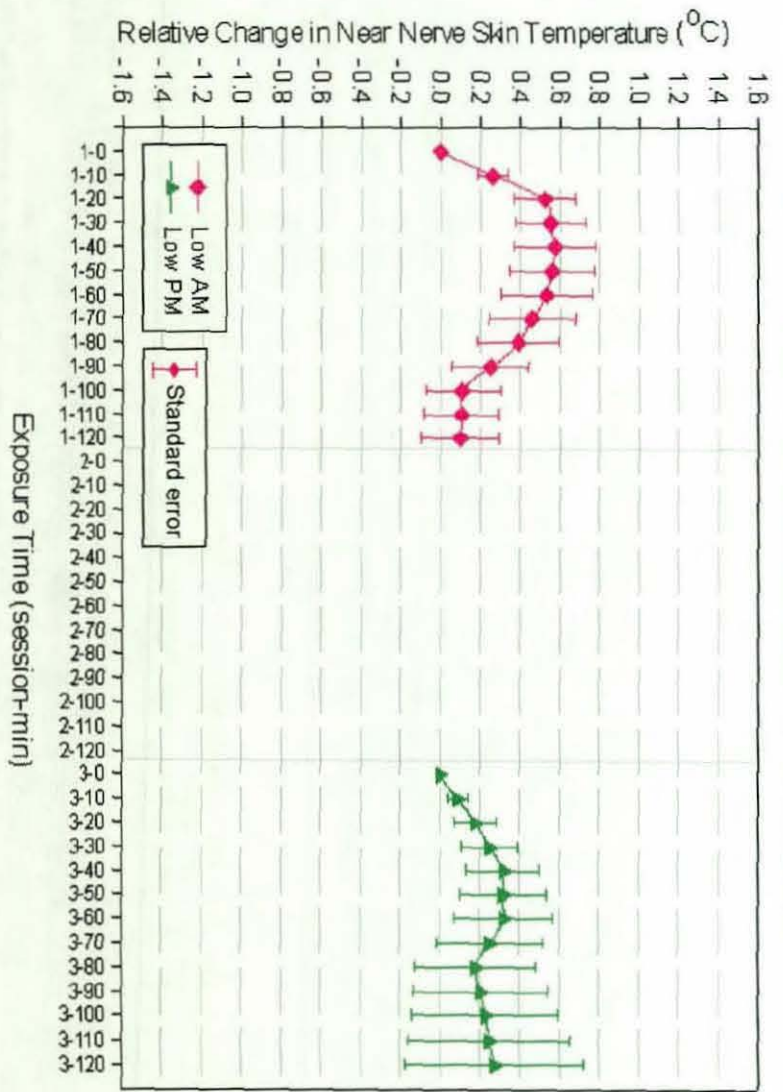
Figure 99: Relative change in wrist temperature – Low
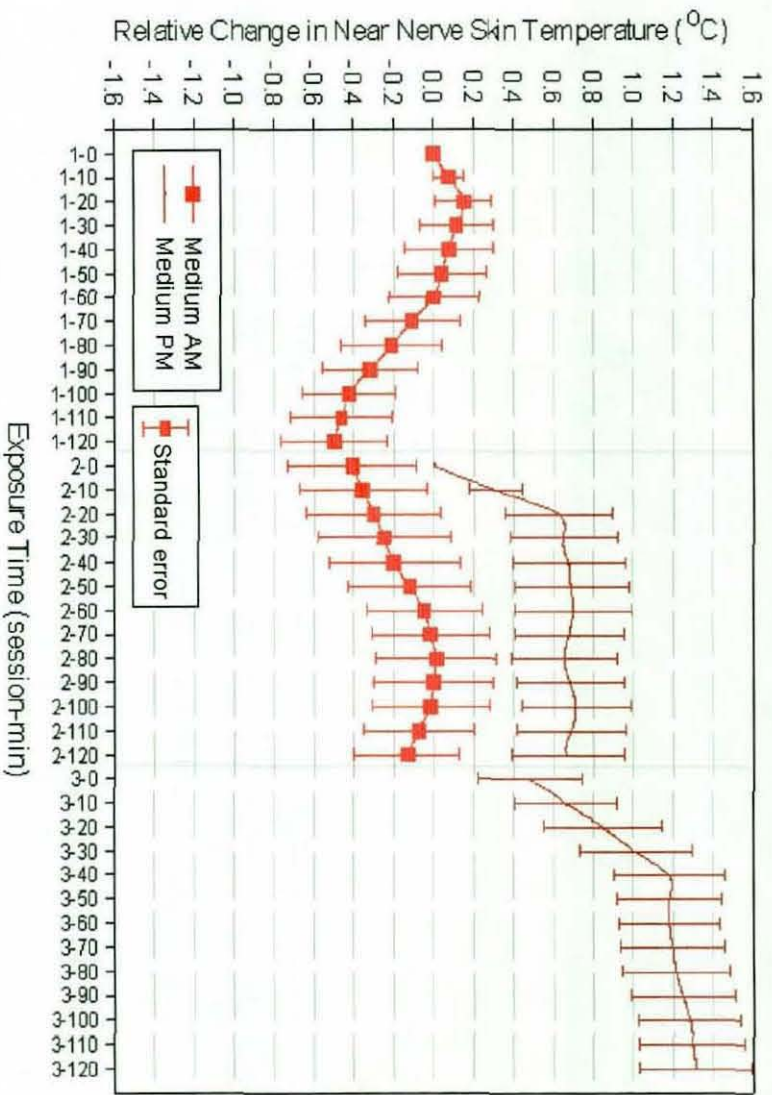
Figure 100: Relative change in wrist temperature – Medium
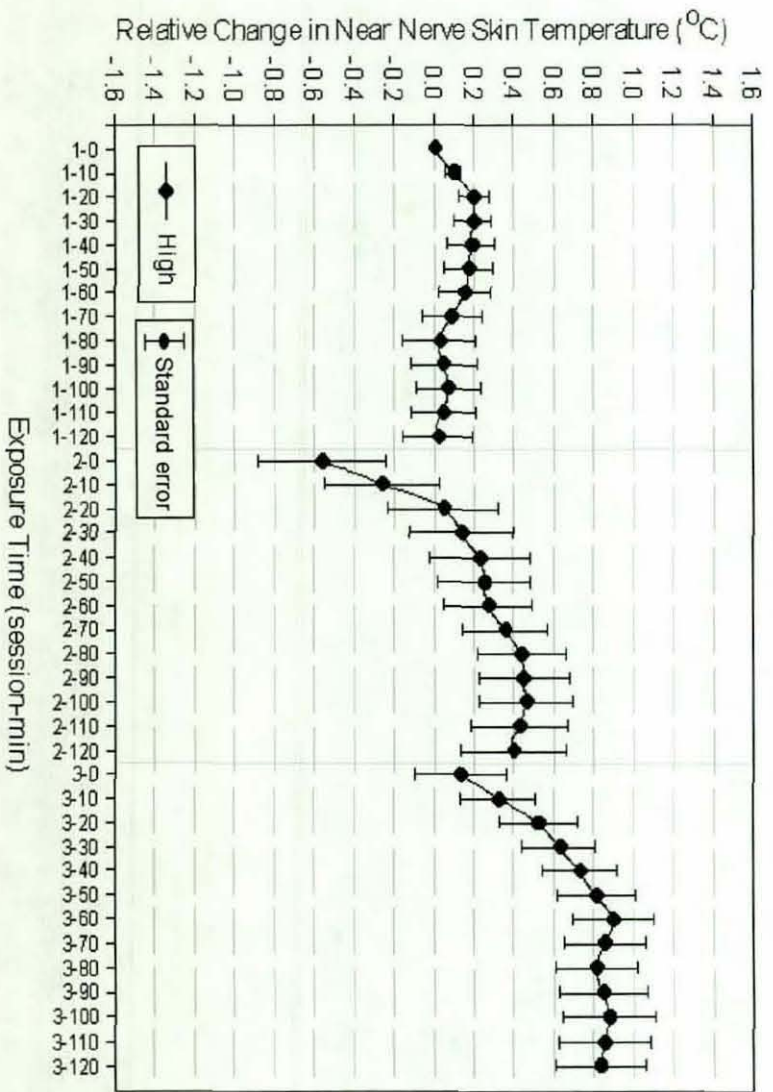
Figure 101: Relative change in wrist temperature – High

5.5.2 Hand Temperature

Near-nerve skin temperature measured at the hand (Figures 102-105) appears to be more sensitive to magnitude and duration of exposure than NNST wrist measures. A similar between session effect is observed across conditions. The effect on NNST appears to be most distinct for medium wrist activity (Figure 104), but a corresponding larger standard error of measures is indicative of increased inter-subject variability. Absolute data are presented in Appendix 6E, Table 2.

Figure 102: <u>Relative change in hand temperature – Static</u>
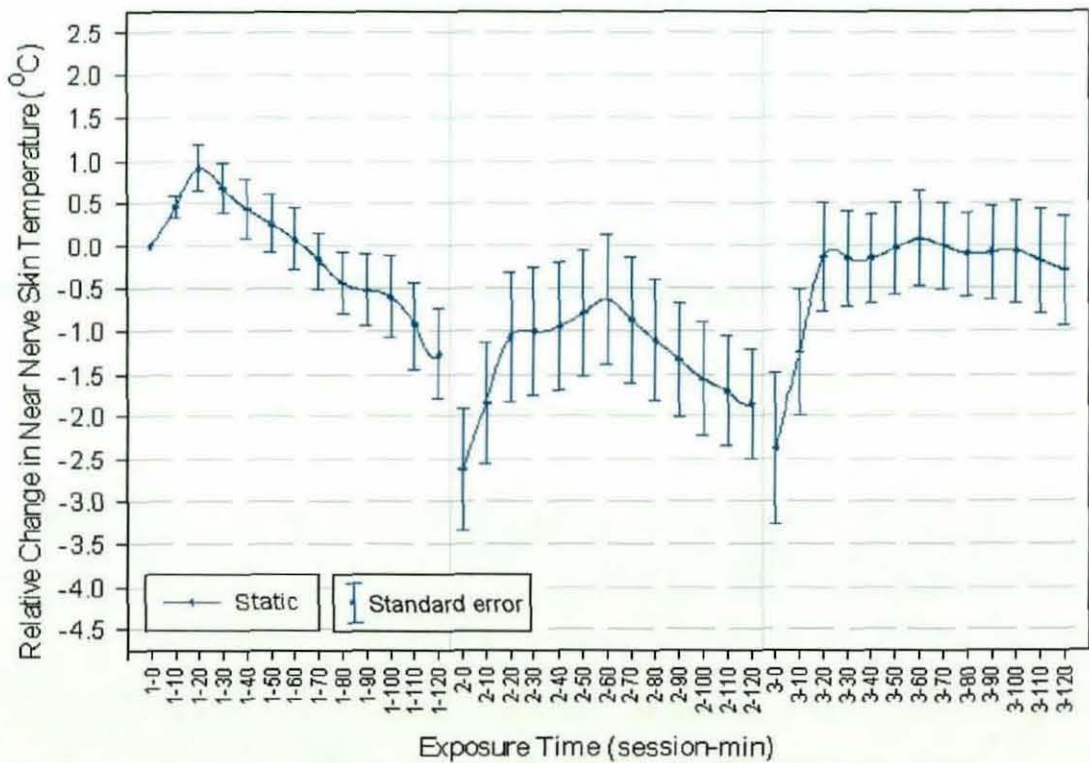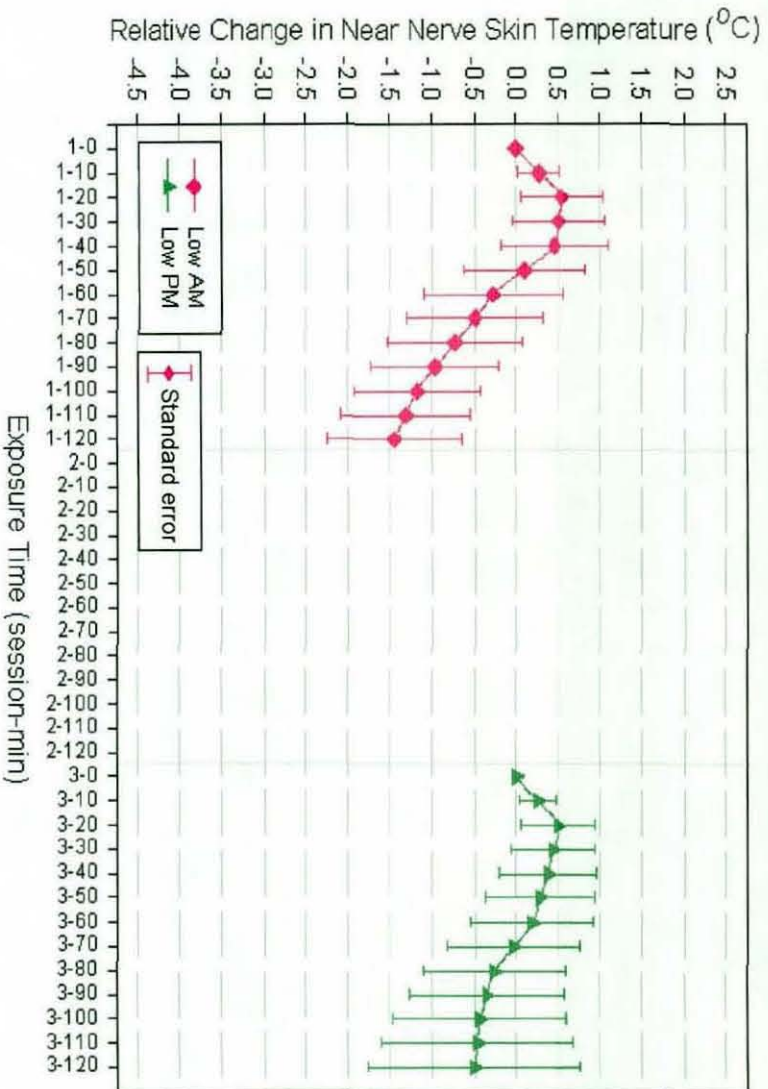
Figure 103: Relative change in hand temperature – Low
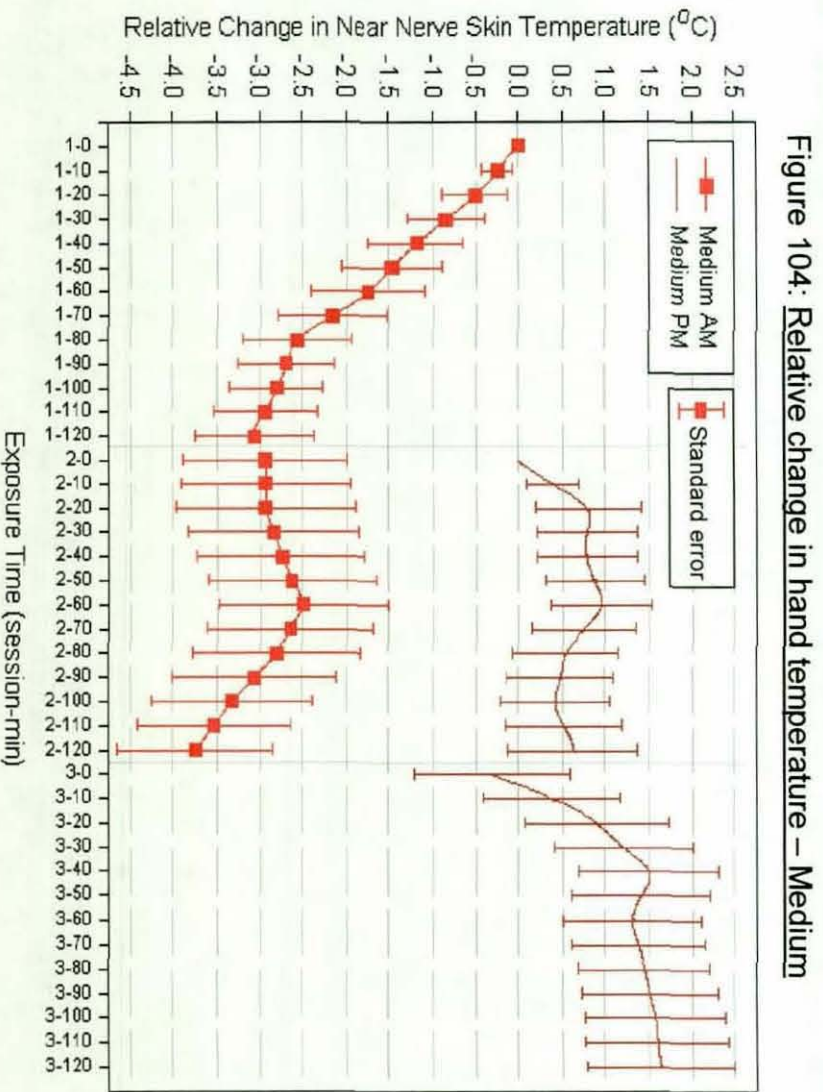
Figure 104: Relative change in hand temperature – Medium

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Figure 105: <u>Relative change in hand temperature – High</u>
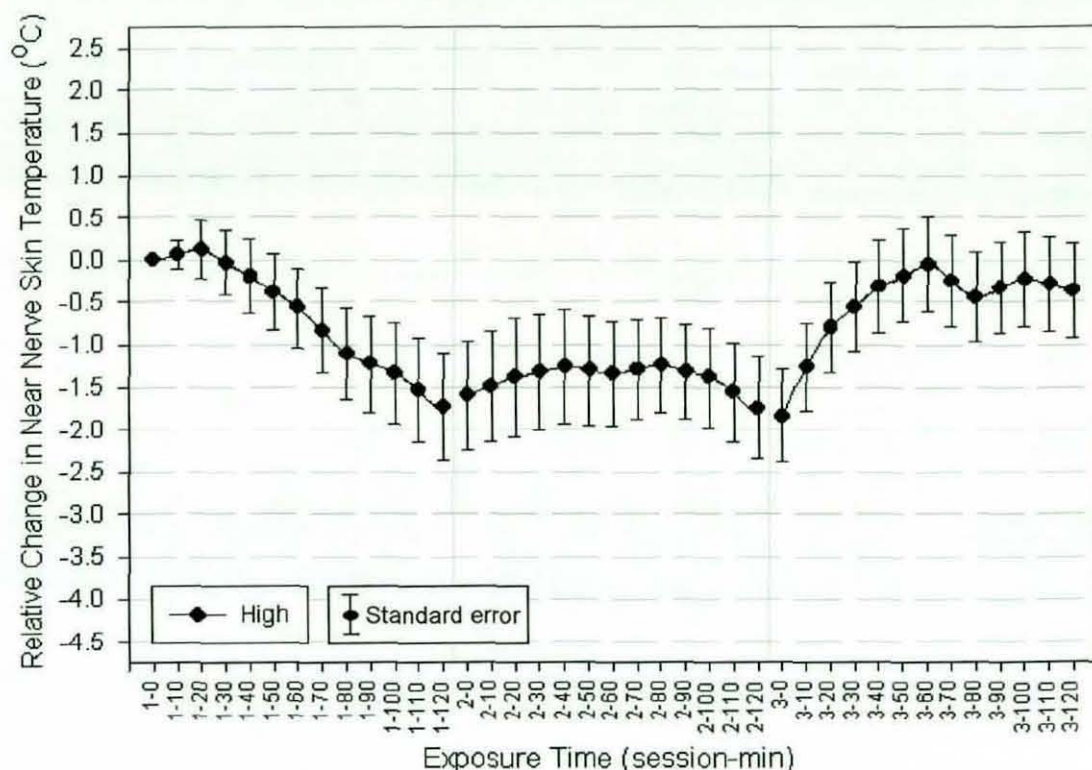
5.5.3 Fingertip Temperature

Near-nerve skin temperature measured at the fingertip (Figures 106-109) appears to be the most sensitive of all NNST measures, where a range of 7.0 °C is noted between conditions.

NNST tends to decrease during the first session, is relatively unchanged between endpoints of the second session and increases during the third session. Again, medium wrist activity (Figure 108) appears to be the most effective on NNST. The corresponding larger standard error of measures (3.0°C) is suggestive of high inter-subject variability. Absolute data are included in Appendix 6E, Table 3.

Figure 106: <u>Relative change in fingertip temperature – Static</u>
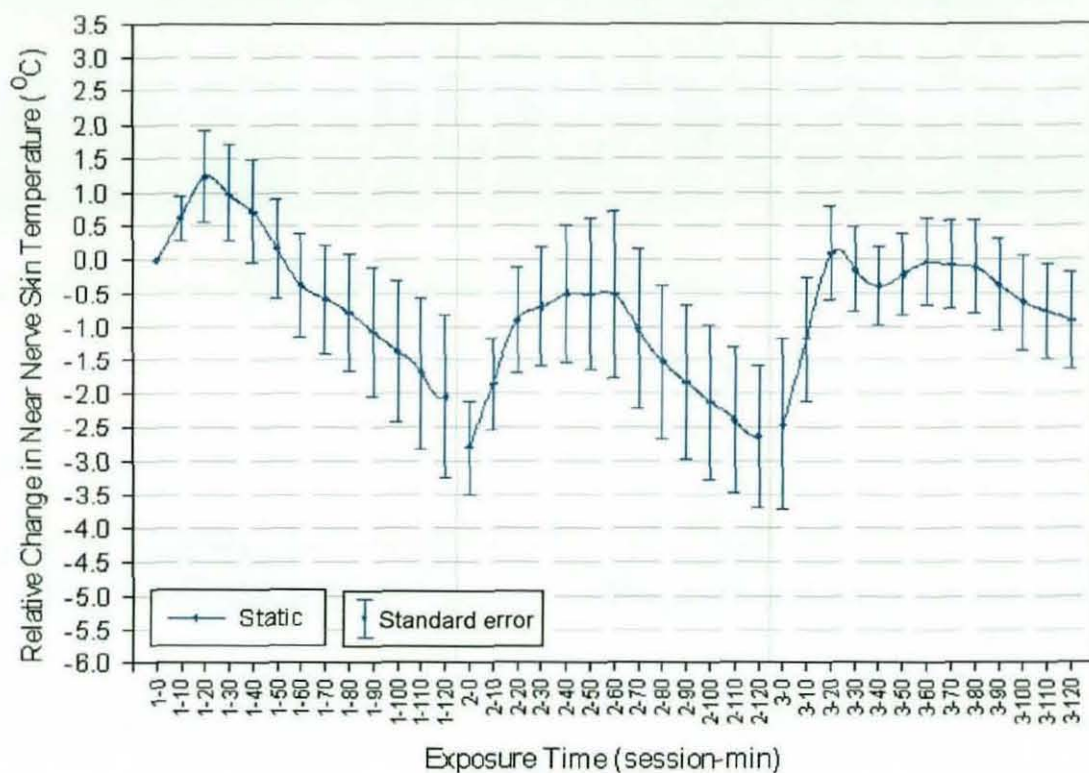
Figure 107: <u>Relative change in fingertip temperature – Low</u>
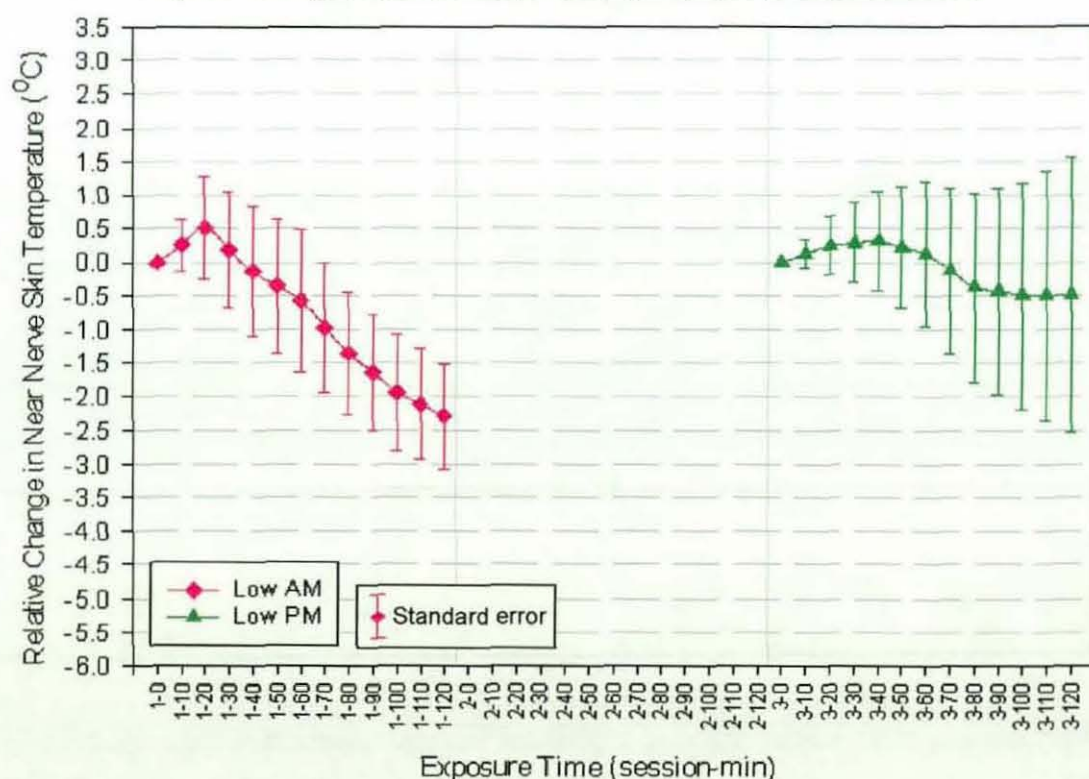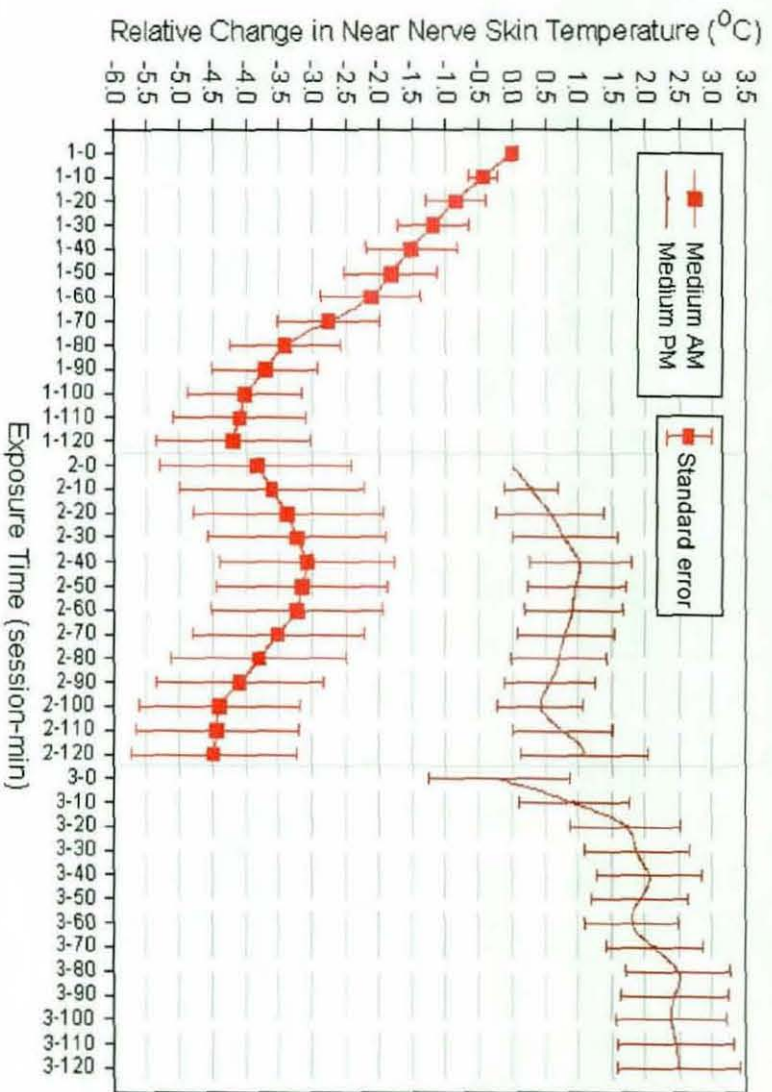
Figure 108: Relative change in fingertip temperature – Medium
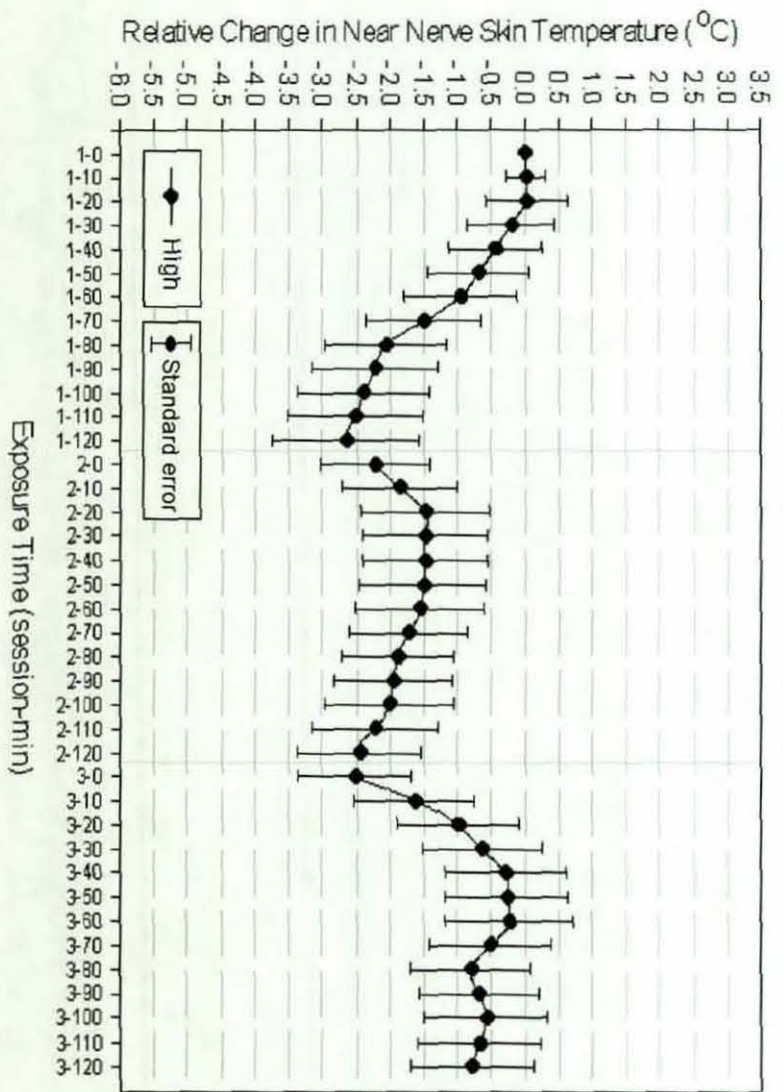
Figure 109: Relative change in fingertip temperature – High

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CHAPTER 6: ANALYSIS OF RESULTS

6.1 Overview of Statistical Analysis

A repeated measures design was employed with subjects serving as their own controls. Parametric analyses of variance (ANOVA) were used to analyze within-subject effects. F-test (variance ratio) resolved for mean effect across subjects. Analyses of covariance (ANCOVA) were utilized to evaluate between-subjects effects. Between conditions effects were examined using repeated measures one-way analyses of variance. Pearson's two-tailed correlation and regression analyses were used to evaluate multi-variate effects and interactions. A summary of research questions, variables, measures and analyses is presented below (Table 12).

For the purpose of this study, statistical significance is recognized at the $\alpha \leq 0.05$ level. The Huynh-Feldt correction was observed. This involves multiplying both the effect and error degrees of freedom by the Huynh-Feldt epsilon to improve Type I error rates (Huynh and Feldt, 1976).

Table 12: Research questions, variables, measures and analyses

Question	Variables	Measurement	Data Analysis
Is there a dose-response relationship between physical stressors imposed on the wrist and response of the median nerve?	1. Sensory median nerve function: a) Onset latency b) Peak latency c) Duration d) Amplitude e) Area f) Conduction velocity 2. Duration of exposure 3. Wrist activity: a) Cycle time b) Angular flexion c) Angular extension d) Range of motion e) Mean angular velocity f) Peak angular velocity g) Mean angular accel h) Peak angular accel i) Linear force j) External work	Distal latencies, impulse duration, amplitudes, area and conduction velocity were recorded using a Nicolet Biomedical electroneurometer. Timeline Wrist activity measured using 3D electromagnetic human motion tracking system (HumanTRAC)	Analysis of variance used to determine the effect of duration of exposure on temperature-adjusted median nerve response for each condition during dynamic wrist motion.

Table 12: Research questions, variables, measures and analyses (continued)

Question	Variables	Measurement	Data Analysis
What duration and magnitude of exposure is required to produce a detectable threshold shift in median nerve function?	1. Sensory median nerve function a) Onset latency b) Peak latency c) Duration d) Amplitude e) Area f) Conduction velocity 2. Duration of exposure	Distal latencies, impulse duration, amplitudes, area and conduction velocity were recorded using a Nicolet Biomedical electroneurometer. Timeline	F-test point-by-point analysis of sensory median nerve function measures against baseline (time=0).
How is the evoked sensory median nerve waveform defined?	1. Sensory median nerve function a) Onset latency b) Peak latency c) Duration d) Amplitude e) Area	Distal latencies, impulse duration, amplitudes and area were recorded using a Nicolet Biomedical electroneurometer.	Descriptive statistics Graphic representation of evoked transformation
Can models be developed to predict median nerve neuropathy as a function of physical and personal risk factors?	1. Sensory median nerve function 2. Wrist activity 3. Room temperature 4. Near-nerve skin temperature 5. Participant demographics 6. Subject anthropometry 7. Medical results	Median nerve function measures recorded using electroneurometer. Wrist activity monitored using 3D electromagnetic tracking system. Room temperature recorded using wall thermometer. Near-nerve skin temperature measured using thermal-resistive skin mounted electrodes. Participant demographics recorded using questionnaires. Subject anthropometry measured during medical evaluation. Medical findings from questionnaires, clinical evaluation, and hematology and radiological examinations.	Regression analyses used to develop predictive equations for sensory median nerve function as a function of significantly correlated physical and personal risk factors.

6.2 Sensory Median Nerve Response

6.2.1 Sensitivity of Objective Measures of Sensory Nerve Function

One-way Analyses of Variance (ANOVAs) were performed across time and conditions for each objective measure of sensory median nerve function (Table 13). Eta-squared (η^2) values were computed (Equation 17) for each ANOVA to determine the proportion of variance that can be explained due to duration of exposure. That is, the percentage of the result that can be explained by the dependent variable. Eta-squared is considered superior to R-squared for this analysis because it considers both linear and non-linear associations.

Equation 17: Eta-squared derivation

$$\eta^2 = \frac{SS_{Between\ Groups}}{SS_{Total}}$$

Table 13: Proportion of variance explained by sensory nerve measures

Condition	Static	Low	Medium	High	MEAN
Onset Latency	0.248	0.254	0.316	0.214	0.258
Peak Latency	0.401	0.40	0.560	0.346	0.427
Duration	0.047	0.167	0.126	0.061	0.100
Amplitude	0.053	0.122	0.149	0.085	0.102
Area	0.080	0.178	0.174	0.123	0.139
Conduction Velocity	0.394	0.393	0.580	0.349	0.429

Blue denotes significance at $\alpha \leq 0.05$
Red denotes significance at $\alpha \leq 0.01$

Results indicate that sensory nerve conduction velocity (as a function of peak latency) is the most sensitive measure of median nerve function over time. Conduction velocity will therefore be used as the major measure of sensory median nerve function throughout the following analyses.

The overall sensitivity of median nerve function measures to duration of exposure in descending order is: (1) conduction velocity, (2) peak latency, (3) onset latency, (4) area, (5) amplitude, and (6) duration. Findings are as expected based on observations (Figures 69-92; Appendix 6B, Tables 2-7).

Given the small effect size difference ($\delta\eta^2=0.002$) between conduction velocity and peak latency, analysis of covariance (ANCOVA) was performed, which revealed that the two dependent variables are statistically undifferentiated across conditions.

6.2.2 Stimulus Level Effect

Stimulus level was determined for each participant at the start of the first day of data collection as that voltage which produced a clearly defined median nerve waveform of amplitude between 20 μV and 40 μV. Once stimulus level was determined, it was maintained across all measures and conditions unless median sensory response deteriorated and was difficult to distinguish from signal artifact.

While it appears that the static and high wrist activity condition participants received a lower stimulus voltage (Figures 65-68; Appendix 6B, Table 1), within-subject comparisons across conditions suggest a similarity between recorded stimulus measures.

Analyses were conducted to ascertain whether variances in stimulus voltage had any effect on nerve conduction. Analyses of Covariance (ANCOVA) were performed for each condition to adjust for effects due to variance in stimulus level. ANOVA was then performed on the residual stimulus level corrected measure of median nerve function (Table 14).

Table 14: <u>Intra session effect of stimulus level</u>

Condition	Source of Variation	SS	DF	MS	F	Sig of F	Power
Static (N=13)	Regression	0.58	1	0.58	0.36	0.550	0.091
	Time	62.75	6	10.46	6.49	**<0.001**	0.998
	Error	114.45	71	1.61			
Low (N=26)	Regression	3.93	1	3.93	0.83	0.364	0.148
	Time	181.66	6	30.28	6.38	**<0.001**	0.999
	Error	707.05	149	4.75			
Medium (N=26)	Regression	0.01	1	0.01	0.00	0.996	0.050
	Time	62.60	6	10.43	3.02	0.08	0.900
	Error	514.06	149	3.45			
High (N=26)	Regression	3.08	1	3.08	1.14	0.287	0.186
	Time	214.20	6	35.70	13.25	**<0.001**	0.999
	Error	401.37	149	2.69			

Red denotes significance at $\alpha \leq 0.01$ level

Analyses of Covariance (ANCOVA) were unsuccessful in adjusting sensory median nerve conduction velocity scores for differences due to stimulus level at any wrist activity level. Stimulus level, therefore, had no significant within-subject effect on sensory median nerve response.

6.3 Room Temperature

6.3.1 Correlations between Room Temperature and SNCV

Pearson's correlation analyses were performed between room temperature (Figure 97) and change in sensory median nerve conduction velocity (Figures 89-92), across participants, conditions and sessions. The following results were derived (Table 15).

Table 15: Correlation analysis between room temperature and SNCV

Session		Static	Low AM	Medium AM	Medium PM	High
1	Pearson Correlation	0.265	-0.83	0.223		0.215
	Sig. (2-tailed)	0.381	0.769	0.510	/	0.291
	N	13	15	11		26
2	Pearson Correlation	0.320		-0.246	-0.287	0.026
	Sig. (2-tailed)	0.286	/	0.467	0.299	0.90
	N	13		11	15	24
3	Pearson Correlation	-0.475			0.124	0.321
	Sig. (2-tailed)	0.101	/	/	0.660	0.127
	N	13			15	24

Results indicate that the association between room temperature and sensory nerve conduction velocity is not significant at $p \leq 0.050$. Strict environmental controls that were instituted throughout the study were effective.

6.4 Near Nerve Skin Temperature

6.4.1 Correlations between Near Nerve Skin Temperature and SNCV

The general pattern of the skin temperature graphs (Figures 98-109) appears to be similar to that of sensory median conduction velocity (Figures 89-92), suggesting a possible association between measures. Correlation analyses were performed between measures of near-nerve skin temperature (NNST) and nerve conduction velocity across participants and sessions, using the Pearson's two-tailed technique. The following results were attained (Table 16).

Table 16: <u>Correlation analyses between skin temperature and SNCV</u>

Skin Temp		Static	Low	Medium	High	Overall
Wrist	Pearson Correlation	0.706	0.417	0.626	0.421	0.566
	Sig. (2-tailed)	$6.98\ e^{-07}$	0.034	$7.09\ e^{-07}$	0.032	$1.47\ e^{-13}$
	N	38	26	52	26	142
Hand	Pearson Correlation	0.810	0.571	0.833	0.707	0.746
	Sig. (2-tailed)	$2.31\ e^{-11}$	0.011	$2.22\ e^{-14}$	$2.32\ e^{-4}$	$4.78\ e^{-19}$
	N	38	19	40	22	119
Fingertip	Pearson Correlation	0.909	0.582	0.833	0.631	**0.747**
	Sig. (2-tailed)	$1.39\ e^{-16}$	0.007	$2.7\ e^{-14}$	0.002	**$4.6\ e^{-19}$**
	N	38	20	40	22	**120**

Blue denotes significance at $\alpha \leq 0.05$ level
Red denotes significance at $\alpha \leq 0.01$ level

Findings were significant for all NNST measurement sites. As put forward based on graphical observations, near-nerve skin temperature measured at the fingertip presents the strongest correlation with sensory median nerve conduction velocity across conditions (R^2=0.558), where SNCV decreases as NNST decreases.

6.4.2 Analysis of Covariance between Fingertip NNST and SNCV.

Analyses of Covariance were performed between fingertip measured near-nerve skin temperature (Figures 106-109) and sensory nerve conduction velocity (Figures 89-92), across participants and sessions for each condition. This test was performed to determine the impact of near-nerve skin temperature on sensory nerve conduction velocity. The following results were attained (Tables 17):

Table 17: <u>ANCOVA between fingertip temperature and SNCV</u>

Condition	Source of Variation	SS	DF	F	Sig of F	ETA Squared	Power
Static	Regression	374.55	1	347.32	**0.000**	0.435	1.000
	Time	9.71	12	0..75	0.702	0.011	0.443
	Error	477.73	443				
Low	Regression	196.08	1	63.18	**0.000**	0.198	1.000
	Time	89.82	12	2.41	**0.006**	0.091	0.964
	Error	704.44	227				
Medium	Regression	511.17	1	270.64	**0.000**	0.360	1.000
	Time	49.64	12	2.19	**0.011**	0.035	0.948
	Error	859.39	455				
High	Regression	646.99	1	446.54	**0.000**	0.364	1.000
	Time	54.21	12	3.12	**0.000**	0.030	0.994
	Error	1076.52	743				

Blue denotes significance at $\alpha \leq 0.05$ level
Red denotes significance at $\alpha \leq 0.01$ level

Results indicate that the confounding effect of near nerve skin temperature is highly significant and can be removed from the dependent variable to produce a temperature corrected SNCV residual.

6.5 Temperature Corrected Sensory Nerve Conduction Velocity

Using analysis of covariance, temperature-adjusted residuals of sensory nerve conduction velocity were computed for each participant, session and condition. Results are presented graphically, by condition (Figures 110-113). Scales for relative change in SNCV are standardized between conditions to facilitate comparative visual analysis.

Based on observation, it would appear that temperature-adjusted SNCV increases across time for the static and low-AM wrist activity conditions (Figures 110 and 111), is relatively unchanged for the low-PM and medium conditions (Figures 111 and 112), and decreases as a function of duration of exposure for the high wrist activity level (Figure 113).

Figure 110: <u>Relative Change in Temperature Corrected SNCV – Static</u>
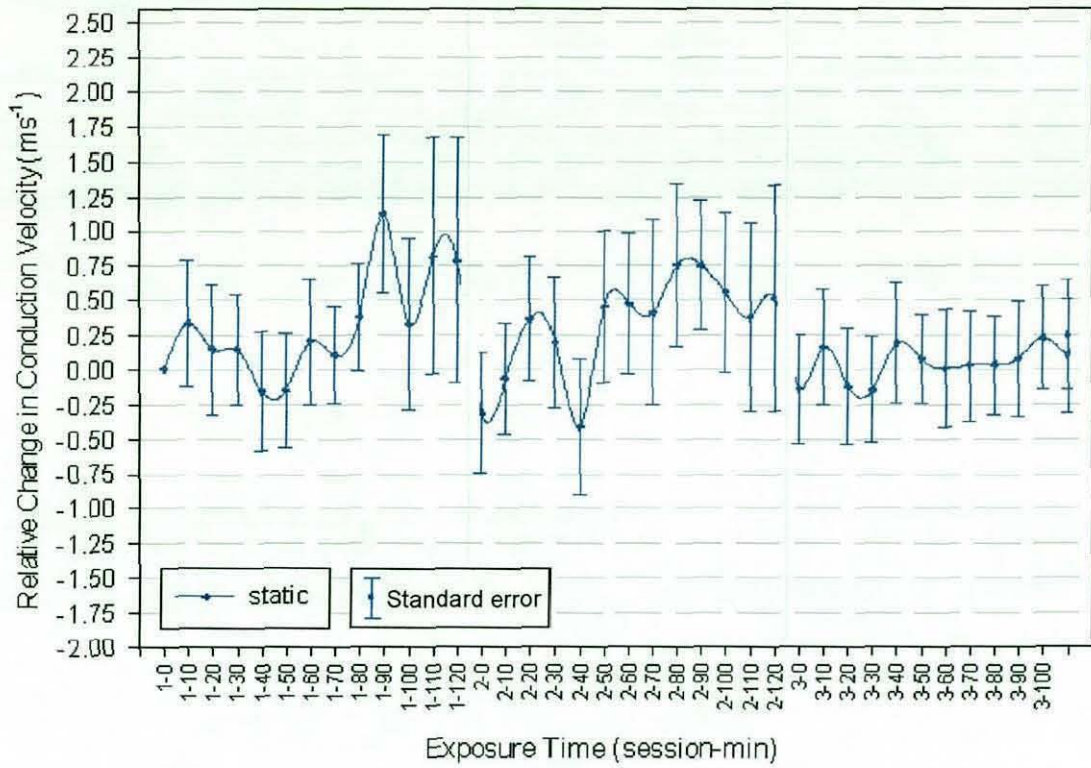
Figure 111: <u>Relative Change in Temperature Corrected SNCV – Low</u>
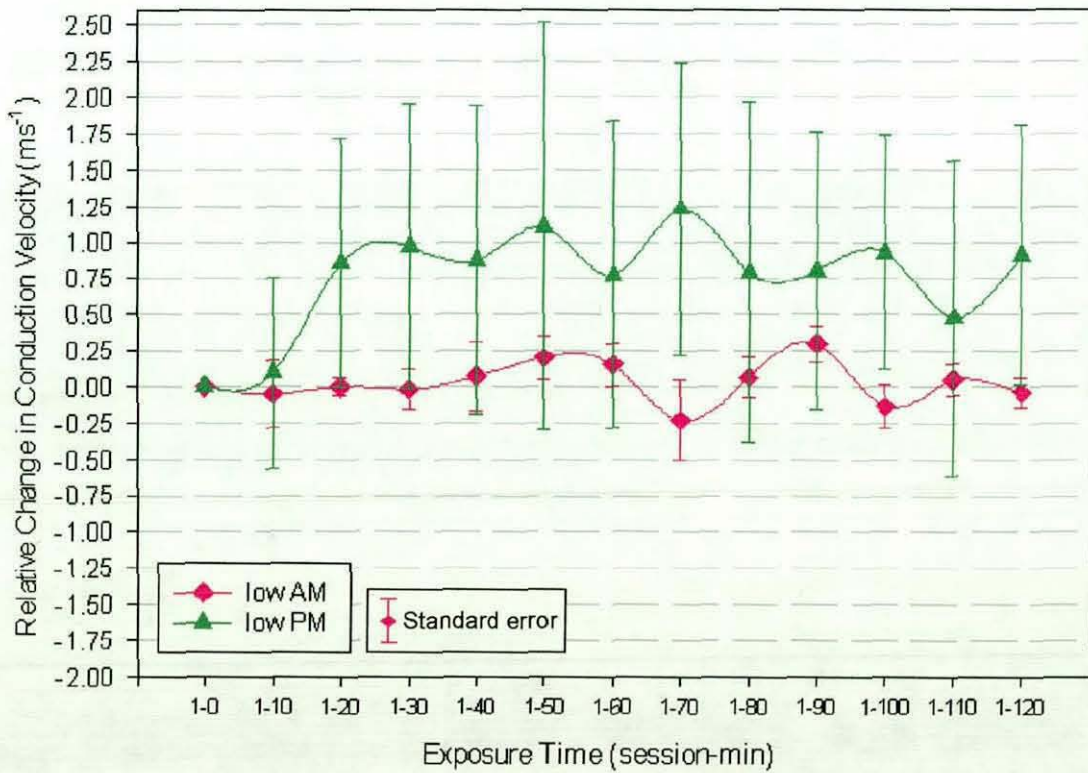
Figure 112: <u>Relative Change in Temperature Corrected SNCV – Medium</u>
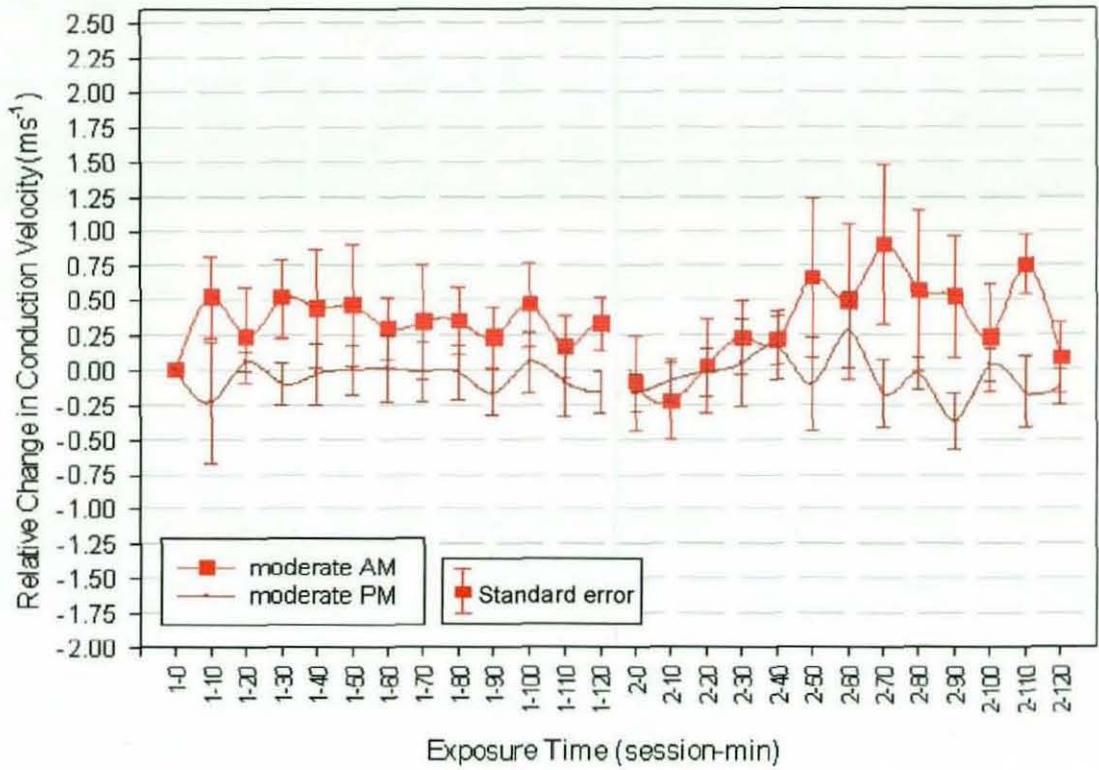
Figure 113: <u>Relative Change in Temperature Corrected SNCV – High</u>
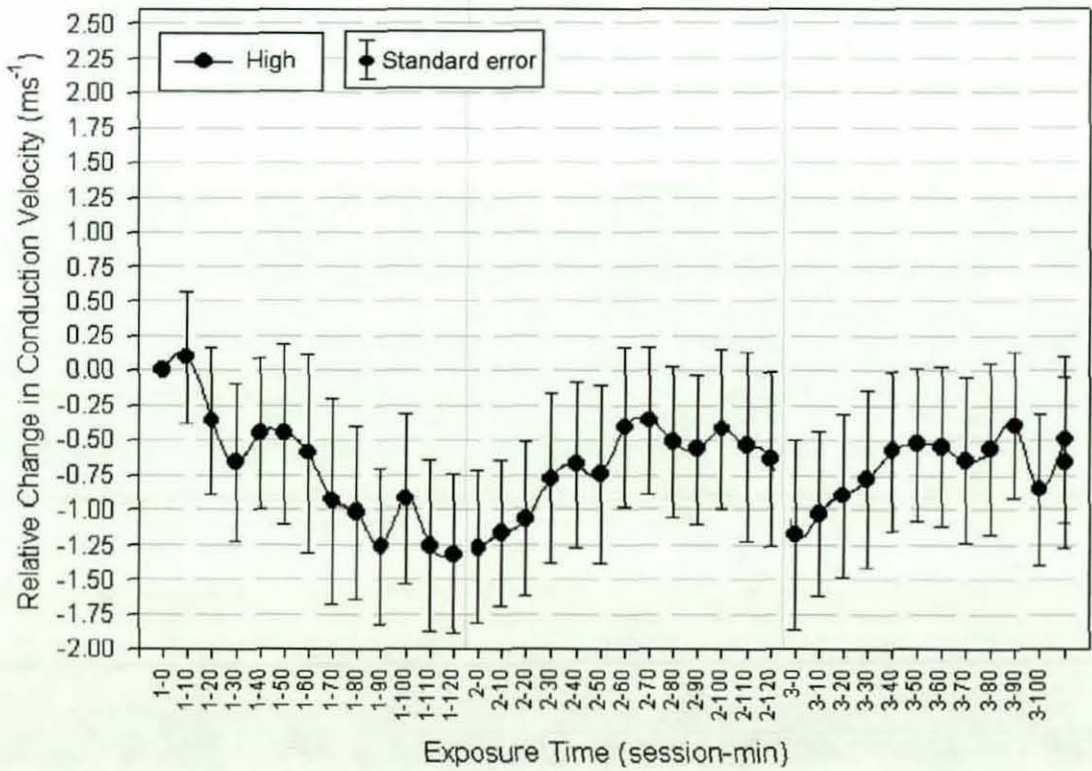
6.5.1 Inter-Session Effects

Temperature-adjusted measures of sensory nerve conduction velocity were analyzed by session. If statistically undifferentiated, data could be combined for subsequent analysis.

Inter-session effects were analyzed for the static, medium and high wrist activity levels, as these conditions required performance of the same task throughout multiple intra-day sessions.

Static Condition: session 1 (N=13); session 2 (N=13); session 3 (N=12)

Figure 114: Temperature corrected SNCV, by session – Static
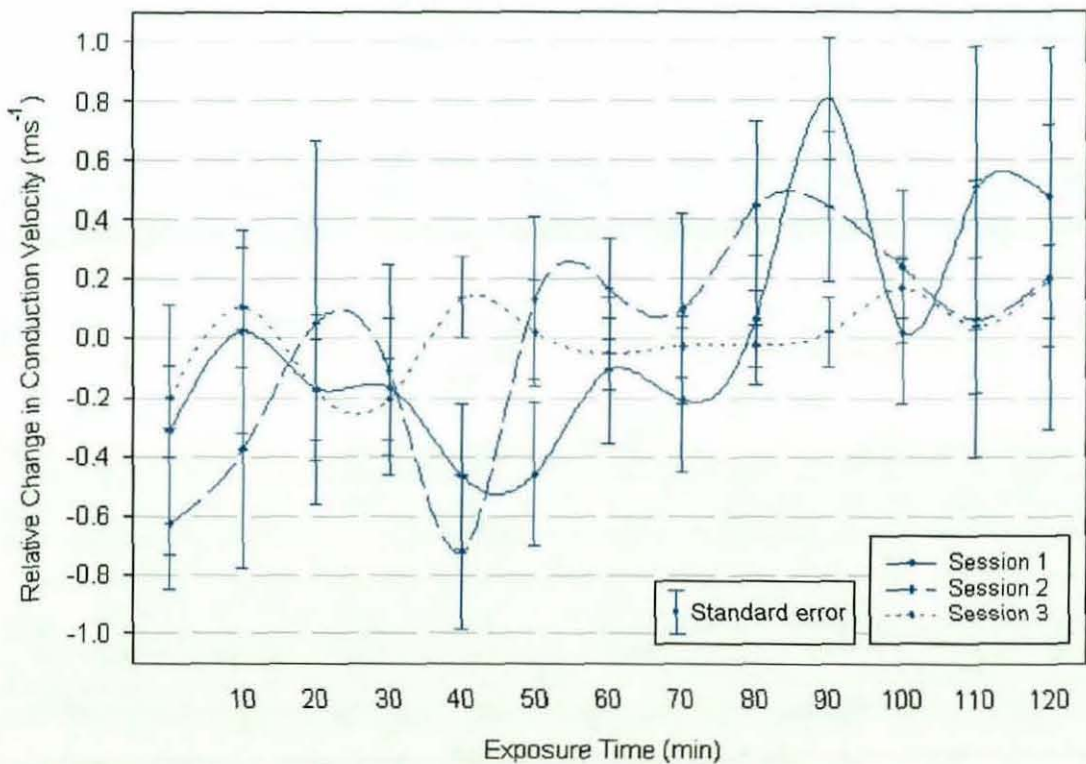
Main Effect of Session:

Considering the main effect of session for the static condition (Figure 114, Table 18), Analysis of Variance for within-subject effect finds:

Table 18: Analysis of variance for within-subject effect – Static

Source of Variation	SS	DF	MS	F	Sig of F	Power
Session	$8.12\ e^{-6}$	2	$4.06\ e^{-6}$	0.635	0.539	0.143
Error (Session)	$1.41\ e^{-4}$	22	$6.40\ e^{-6}$			
Time	16.848	12	1.404	1.068	0.392	0.595
Error (Time)	173.552	132	1.315			
Session x Time	18.854	24	.786	0.786	0.754	0.662
Error (Time x Session)	264.0	264	1.000			

A significant effect of session or time by session interaction was not detected. Sessions 1 through 3 for the static condition may be combined for further analysis, resulting in N=38.

Medium Wrist Activity Condition (N=20); session 1 (N=8); session 2 (N=12)

Figure 115: Temperature corrected SNCV, by session – Medium
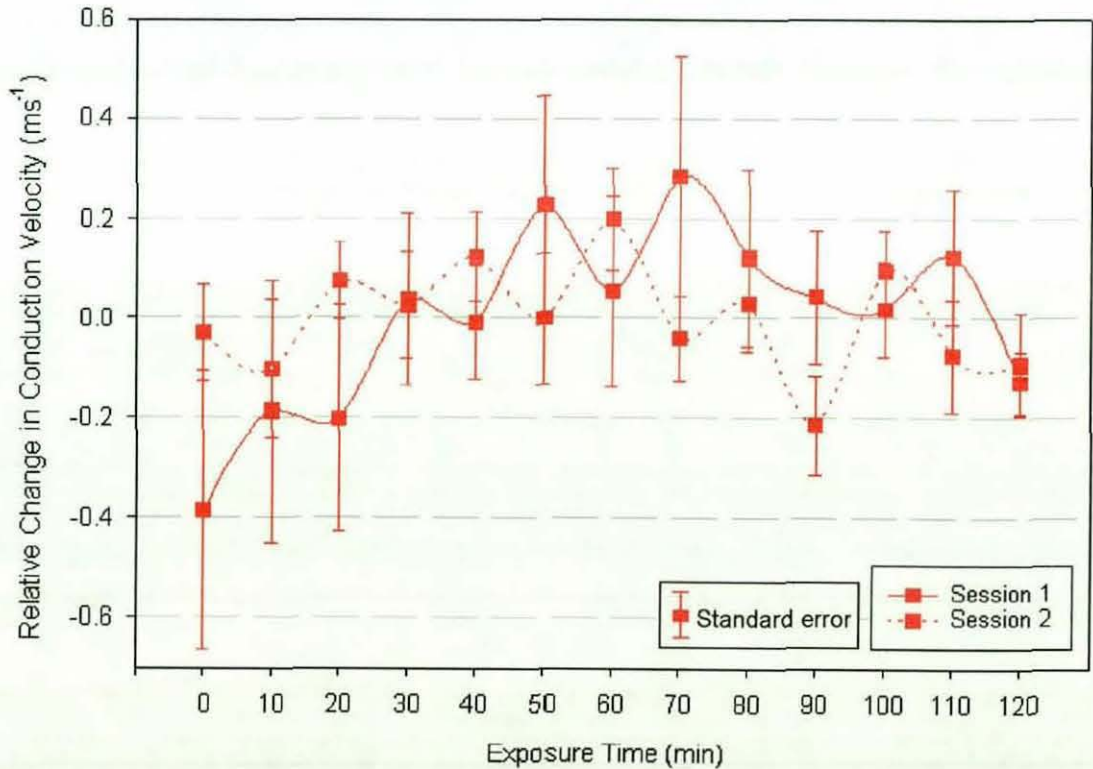
Main Effect of Session:

Considering the main effect of session for the medium condition (Figure 115, Table 19), Analysis of Variance for within-subject effect finds:

Source of Variation	SS	DF	MS	F	Sig of F	Power
Session	$4.81\,e^{-7}$	1	$4.81\,e^{-7}$	0.52	0.826	0.055
Error (Session)	$6.49\,e^{-5}$	7	$9.27\,e^{-6}$			
Time	6.549	12	0.546	0.806	0.644	0.432
Error (Time)	56.889	84	0.677			
Session x Time	6.973	12	0.581	1.003	0.453	0.539
Error (Time x Session)	48.649	84	0.579			

A significant effect of session or time by session interaction was not detected. Sessions 1 and 2 for the medium condition may therefore be combined, resulting in N=20.

High Wrist Activity: session 1 (N=22); session 2 (N=21); session 3 (N=21)

Figure 116: Temperature corrected SNCV, by session – High
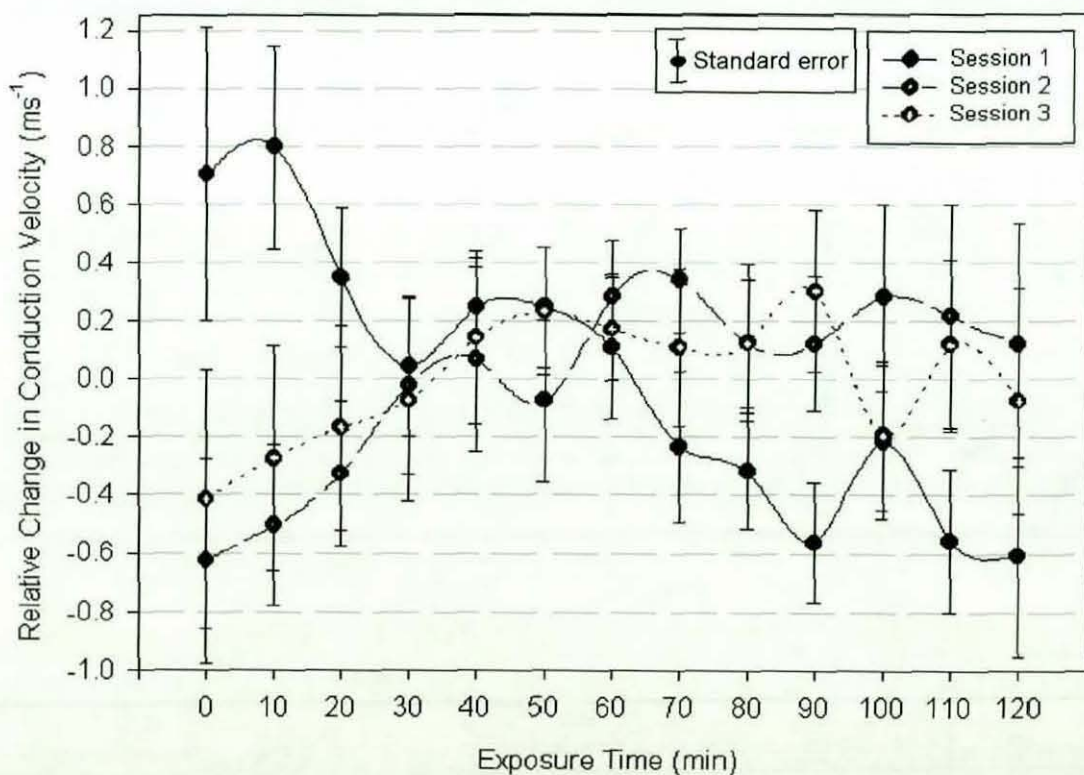
Main Effect of Session:

Considering first the main effect of session for the high condition (Figure 116, Table 20), Analysis of Variance for within-subject effect finds:

Table 20: <u>Analysis of variance for within-subject effect – High</u>

Source of Variation	SS	DF	MS	F	Sig of F	Power
Session	$9.82\ e^{-6}$	2	$9.10\ e^{-6}$	0.636	0.535	0.149
Error (Session)	$3.09\ e^{-4}$	40	$7.72\ e^{-6}$			
Time	8.553	12	0.713	0.290	0.991	0.168
Error (Time)	589.899	240	2.458			
Session x Time	64.936	24	2.706	1.542	**0.050**	0.968
Error (Time x Session)	842.407	480	1.755			

Blue denotes significance at $\alpha \leq 0.05$ level

A significant effect of session-by-time interaction was detected. Further analysis is warranted to determine which sessions are statistically different.

Session by Time Interaction:

The function of the session-by-time interaction was further analyzed to determine which session interactions were significant (Table 21).

Table 21: <u>Analysis of variance for session by time interaction – High</u>

Session	Source	SS	DF	MS	F	Sig	Power
1 vs 2	Session x Time	88.59	1	88.59	5.739	**0.026**	0.625
	Error	308.7	20	15.44			
1 vs 3	Session x Time	2.514	1	2.514	5.413	**0.031**	0.600
	Error	9.287	20	0.464			

Blue denotes significance at $\alpha \leq 0.05$ level

Analysis of Variance involving session-by-time interaction for within-subject contrast finds that session 1 is statistically differentiated from both sessions 2 and 3. Therefore, session 1 for the high wrist activity condition must be analyzed independent of sessions 2 and 3.

6.5.2 Order Effects

Based on the experiment design (refer to Experiment design matrix, Table 6), both the low activity (2 hours @ 22 repetitions per minute) and medium activity (4 hours @ 38 RPM) conditions were performed within the same workday, thereby minimizing time commitment on the part of the subjects. The order in which the tasks were accomplished was randomized to minimize any potential training effect, a possible source of random error. Analyses were performed to investigate whether ordered groups should be treated collectively or independently for subsequent analyses.

Low Wrist Activity Group (N=19); Low AM (N=11); Low PM (N=8)

Figure 117: Temperature corrected SNCV, by order – Low
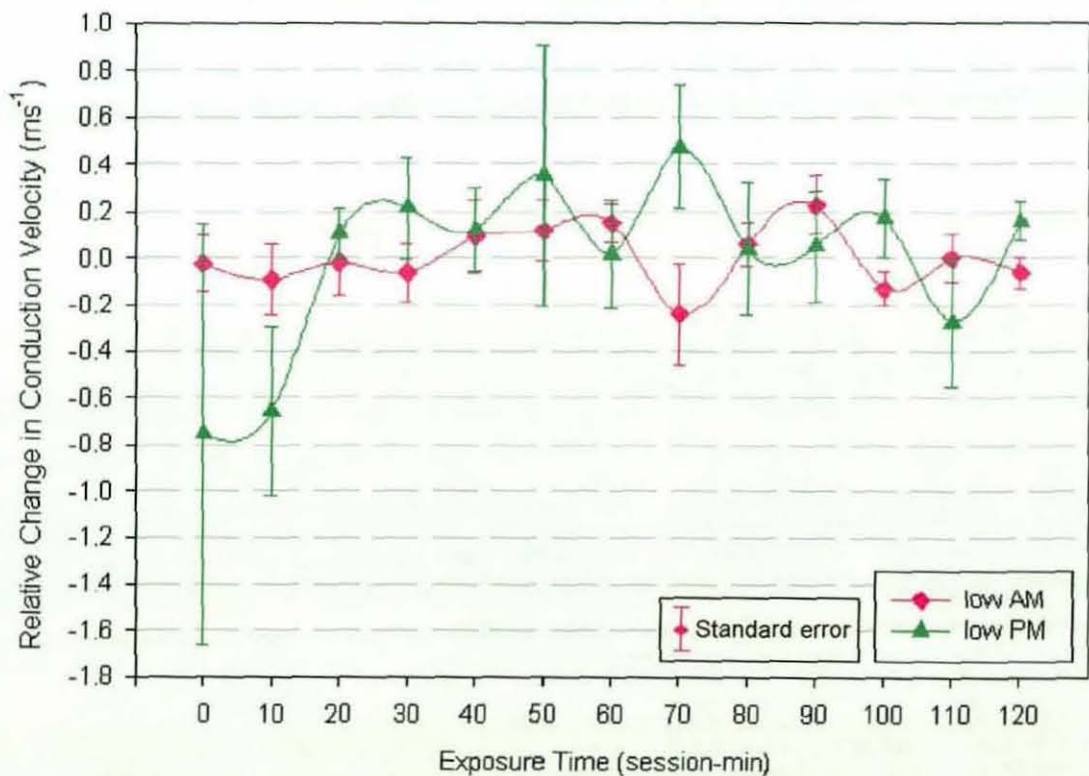
Main Effect of Order

Considering the main effect of order for the low wrist activity condition (Figure 117), analysis of covariance (ANCOVA) was performed to test for a between-groups effect after adjusting temperature-corrected SNCV for order.

ANOVA was then performed on the residual to determine the significance of an order-free measure of nerve conduction velocity (Table 22).

Table 22: <u>Analysis of covariance for order effect – Low</u>

Source of Variation	SS	DF	MS	F	Sig of F	Power
Regression	$8.51\ e^{-6}$	1	$8.51\ e^{-6}$	1.079	0.313	0.165
Order	$2.03\ e^{-6}$	1	$2.03\ e^{-6}$	0.257	0.618	0.077
Error	$1.34\ e^{-4}$	17	$7.88\ e^{-6}$			

ANCOVA was unsuccessful in adjusting sensory median nerve conduction velocity measures for order effects. A significant effect of order between groups was not significant for the low activity condition.

Effect of Time and Time by Order Interaction

A mixed-model Analysis of Variance was performed to investigate the strength of association between sensory nerve conduction velocity and within-subject effects of duration of exposure and time-by-order interaction (Figure 118, Table 23).

Figure 118: <u>Mean effect of time across ordered conditions - Low</u>
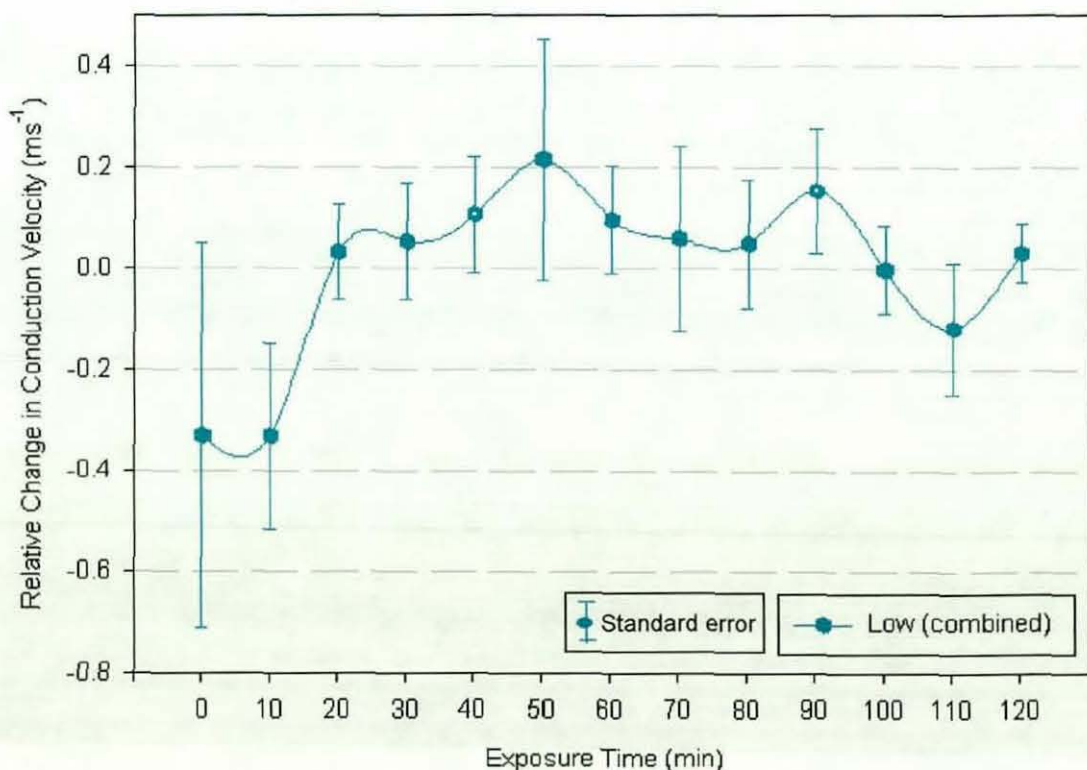
Table 23: <u>Analysis of variance for time-by-order effects – Low</u>

Source of Variation	SS	DF	MS	F	Sig of F	Power
Time	7.963	12	0.664	1.129	0.338	0.640
Error (Time)	119.923	204	0.588			
Time x Order	8.264	12	0.689	1.171	0.306	0.661
Error (Time x Order)	106.08	204	0.520			

Results show that neither the effect of time, nor time-by-order interaction is significant. Ordered conditions at the low wrist activity level are statistically similar and may be combined for subsequent analyses, resulting in N=19.

<u>Medium Wrist Activity Group</u> (N=20); Medium AM (N=8); Medium PM (N=12)

Main Effect of Order

Considering the main effect of order for the medium wrist activity level (Figure 119), analysis of covariance (ANCOVA) was performed to test for a between-groups effect after adjusting temperature-corrected nerve conduction velocity for order. ANOVA was then performed on the residual (Table 24).

Figure 119: <u>Temperature corrected SNCV, by order – Medium</u>
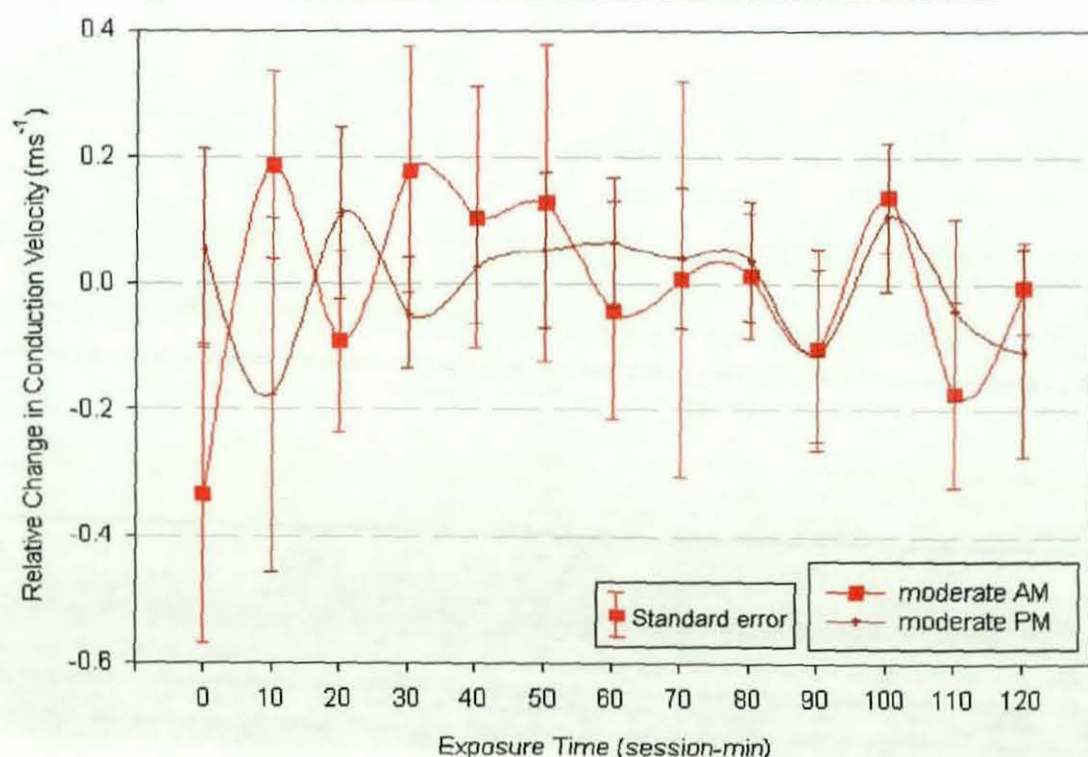
Table 24: <u>Analysis of covariance for order effect – Medium</u>

Source of Variation	SS	DF	MS	F	Sig of F	Power
Regression	$1.26\ e^{-7}$	1	$1.26\ e^{-7}$	0.015	0.905	0.052
Order	$1.24\ e^{-7}$	1	$1.24\ e^{-7}$	0.016	0.904	0.053
Error	$1.54\ e^{-4}$	18	$8.55\ e^{-6}$			

ANCOVA was unsuccessful in adjusting sensory median nerve conduction velocity measures for order effects. A significant effect of order between groups was not significant for the medium wrist activity level.

Effect of Time and Time by Order Interaction

A mixed-model Analysis of Variance was performed to investigate the strength of association between sensory nerve conduction velocity and within-subject effects of duration of exposure and time-by-order interaction (Figure 120, Table 25).

Figure 120: <u>Mean effect of time across ordered conditions - Medium</u>
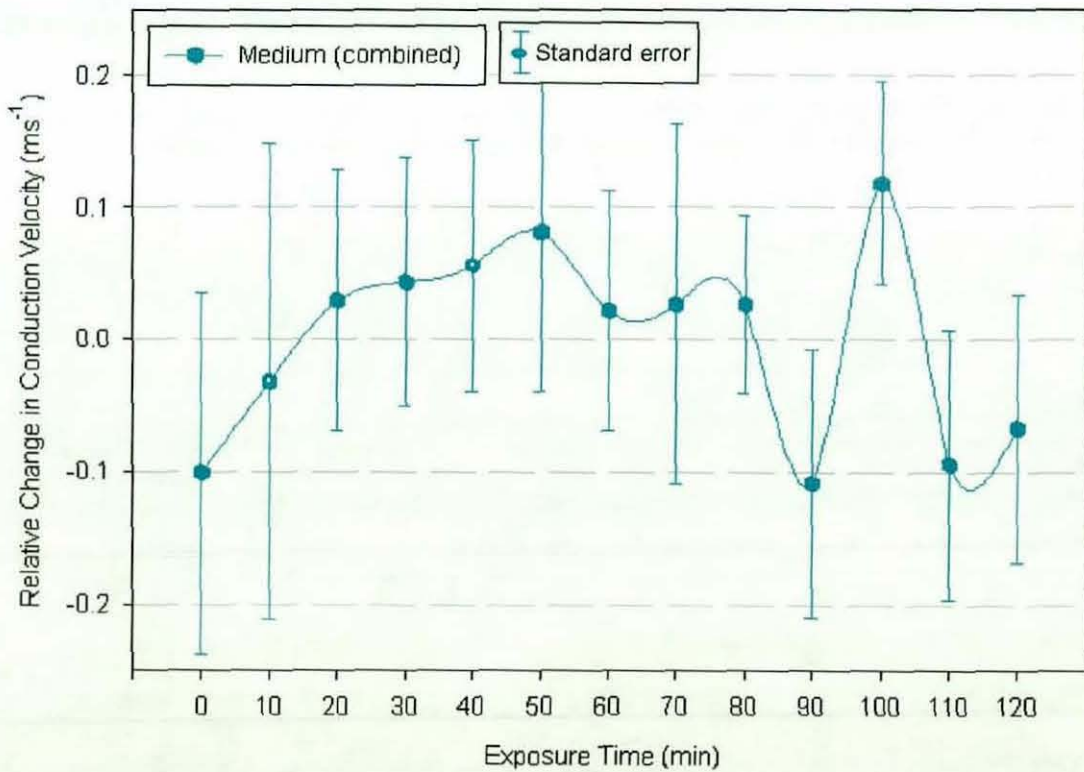
Table 25: <u>Analysis of variance for time-by order-effects – Medium</u>

Source of Variation	SS	DF	MS	F	Sig of F	Power
Time	1.510	12	0.126	0.458	0.937	0.258
Error (Time)	59.394	216	0.275			
Time x Order	2.057	12	0.171	0.623	0.821	0.356
Error (Time x Order)	23.011	216	0.107			

Results show that neither the effect of time, nor time-by-order interaction was significant. Ordered conditions at the medium wrist activity level are statistically similar and may be combined for the purpose of subsequent analysis, resulting in N=40.

6.5.3 Temperature Corrected SNCV across Sessions

Figure 121: <u>Relative change in SNCV by condition, across sessions</u>
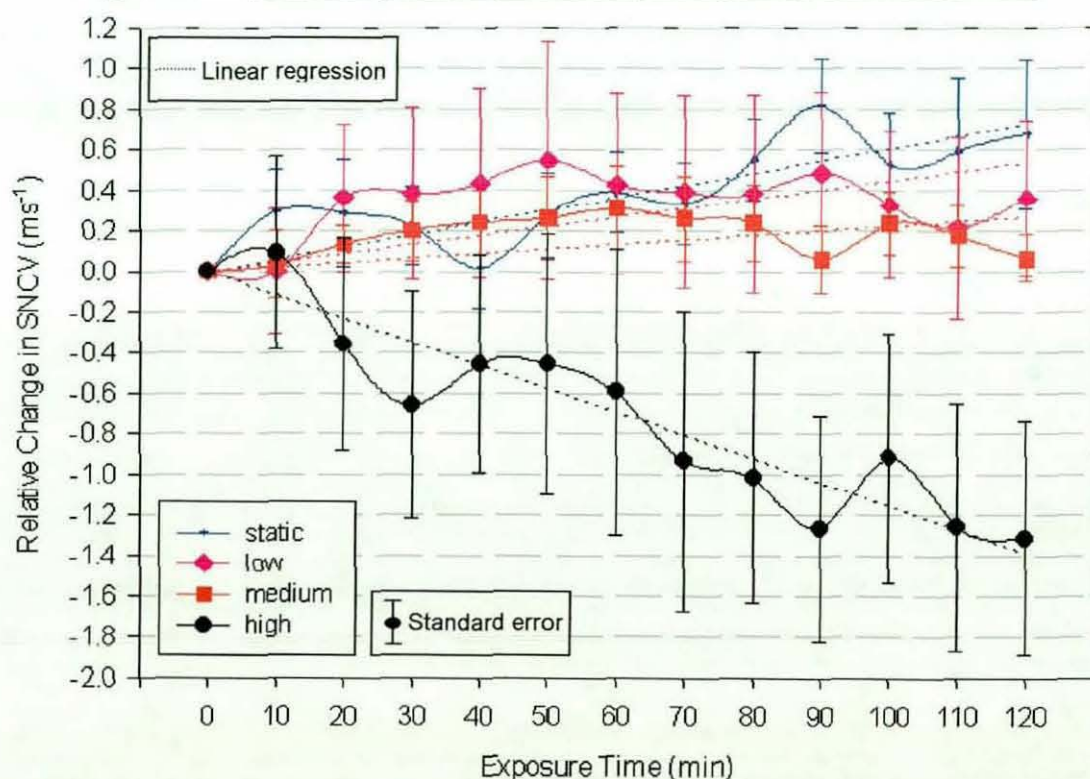
Linear regression plots indicate that there is an increase over time in SNCV for the static, low and medium conditions, while SNCV decreases as a function of duration of exposure for the high wrist activity level.

6.5.4 Effect of Duration of Exposure

Statistical analyses were performed for temperature-corrected sensory nerve conduction velocity at each wrist activity level to determine whether any significant effects of duration of exposure were evident.

Static Condition (N=38)

Figure 122: Relative change in temperature corrected SNCV – Static
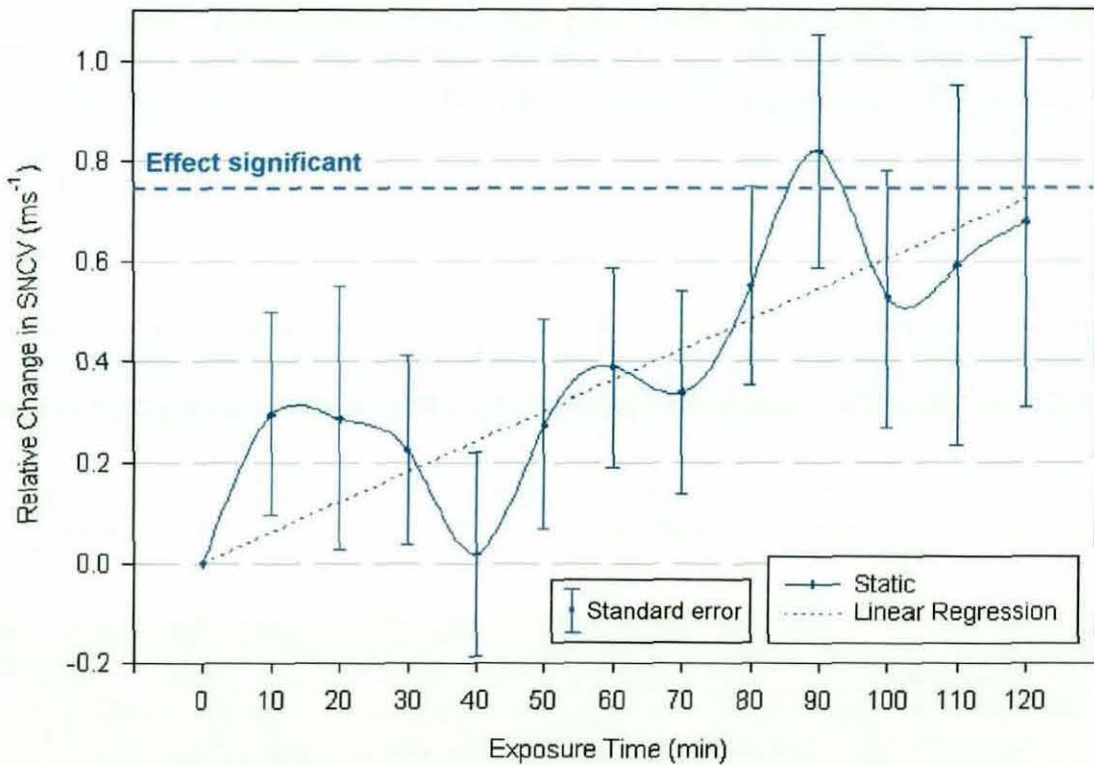
Analysis of Variance test involving duration of exposure for within-subject effect (Figure 122) produced the following result (Table 26):

Table 26: ANOVA involving duration of exposure – Static

Source of Variation	SS	DF	MS	F	Sig of F	Power
Time	26.64	12	2.22	1.90	0.032	0.907
Within cells	518.42	444	1.17			

Blue denotes significance at $\alpha \leq 0.05$ level

A significant within-subject effect of duration of exposure (time) was detected across participants. Equation 18 describes the predictive linear function of the effect of duration of exposure on SNCV for the static condition.

Equation 18: Predictive function for effect of duration of exposure - Static

Expected CV $_{(static)}$ = (0.006)*Time

$R^2 = 0.018$

Where 'Time' is expressed in minutes of exposure to stressor

F-test analyses resolved for duration of exposure where mean effect across subjects was significantly differentiated (p<0.05) from the mean baseline measure (T=0) between T=80 and T=100 (Figure 122). That is, a significant change in sensory median nerve conduction velocity due to static condition is distinguishable from initial measure between these time points. Linear regression of the effect approaches significance at T=120 minutes.

Waveform Shift following two-hours uninterrupted exposure to stressors

The mean waveform shift across participants for the static condition describes the evoked transformation in temperature-corrected sensory median nerve function (Table 27, Figure 123). The empirical upper limit of normal for sensory peak latency (3.48ms - Jackson and Clifford, 1989) is represented, showing that the effect of time, while statistically significant, did not produce electrophysiologic evidence of median nerve neuropathy.

Table 27: Mean waveform descriptors for static condition

Measure	Baseline	Induced	% change
Onset Latency (msec)	2.54	2.53	-0.30
Peak Latency (msec)	3.15	3.10	-1.70
Duration (msec)	0.61	0.57	-7.71
Amplitude (μV)	27.05	24.99	-8.24
Area (μVmsec)	8.90	8.01	-11.07
Conduction Velocity (ms^{-1})	44.72	45.40	+1.51

Figure 123: <u>Mean waveform shift for static condition</u>
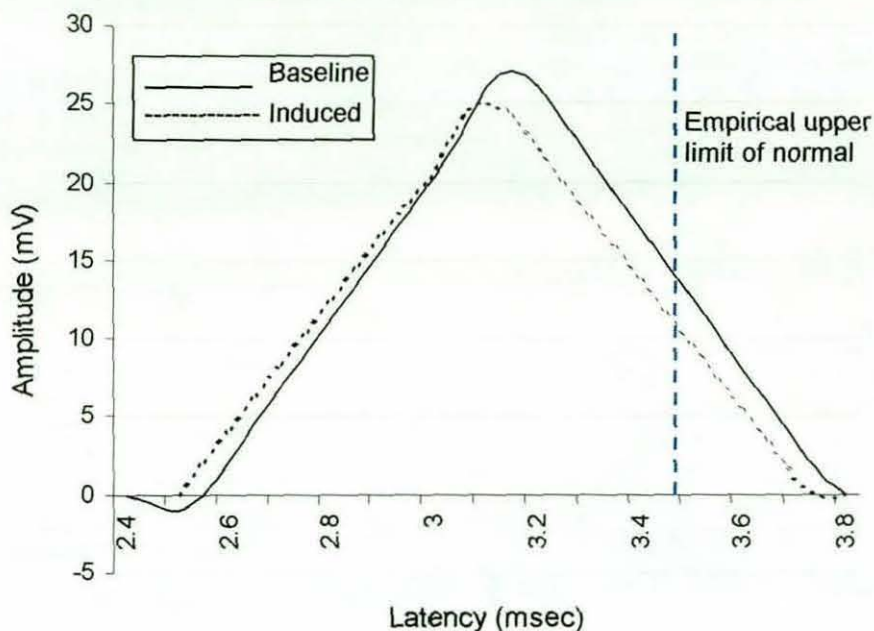
Low Wrist Activity Condition (N=19)

Figure 124: <u>Relative change in temperature corrected SNCV – Low</u>
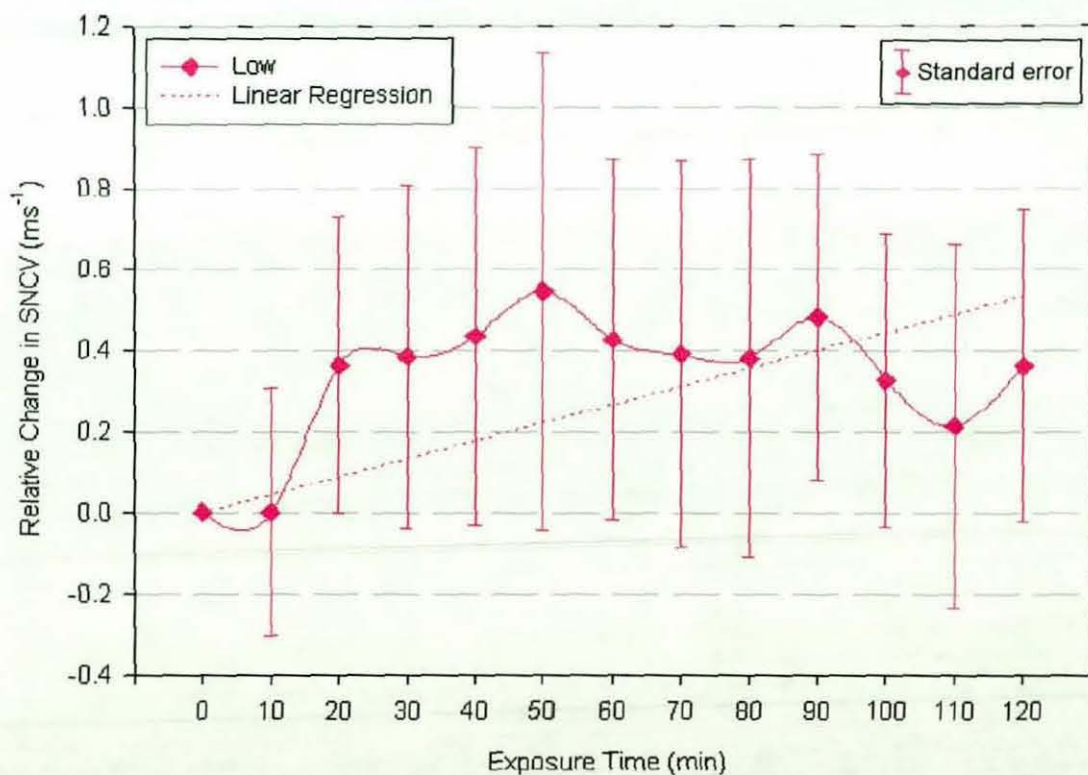
Analysis of Variance involving duration of exposure for within-subject effect (Figure 124) produced the following result (Table 28):

Table 28: <u>ANOVA involving duration of exposure – Low</u>

Source of Variation	SS	DF	MS	F	Sig of F	Power
Time	6.34	12	0.53	0.89	0.449	0.515
Within cells	127.98	216	0.59			

No significant within-subject effect of duration of exposure (time) was detected across participants for the low wrist activity condition.

Medium Wrist Activity Condition (N=40)

Figure 125: <u>Relative change in temperature corrected SNCV – Medium</u>
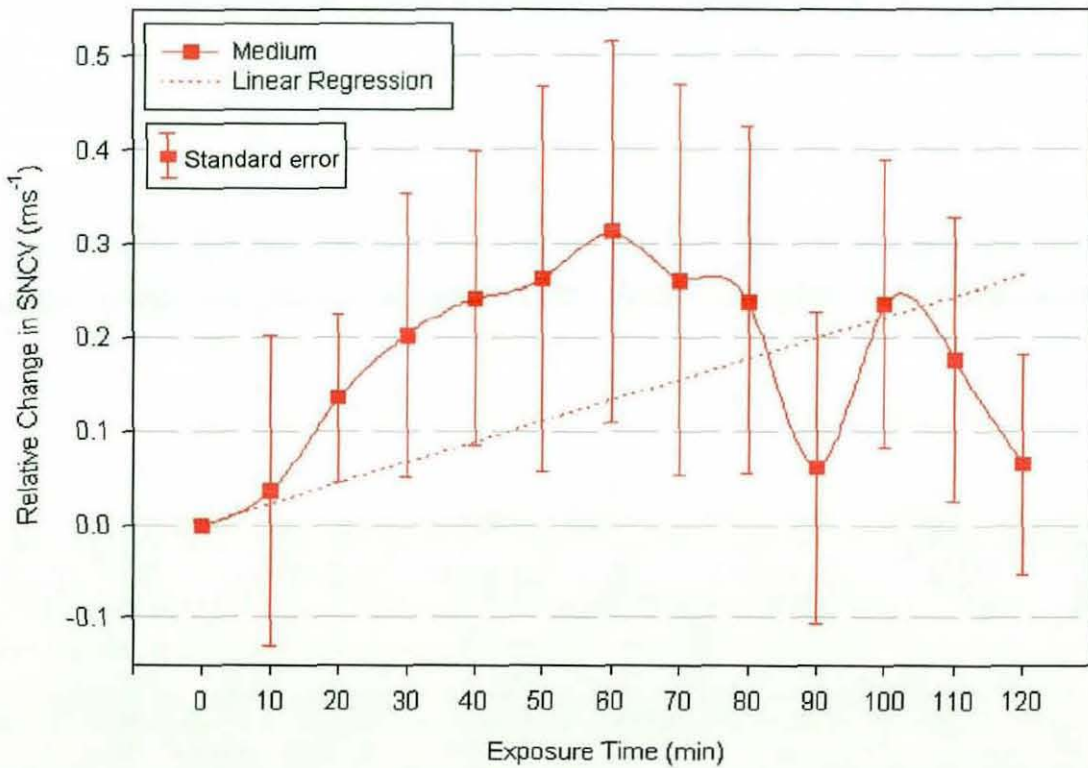
Analysis of Variance involving duration of exposure for within-subject effect (Figure 125) found no significant effect across participants for the medium wrist activity condition. (Table 29):

Table 29: ANOVA involving duration of exposure – Medium

Source of Variation	SS	DF	MS	F	Sig of F	Power
Time	4.95	12	0.41	1.00	0.429	0.587
Within cells	193.68	468	0.41			

High Wrist Activity Condition (N=22)

Figure 126: Relative change in temperature corrected SNCV – High
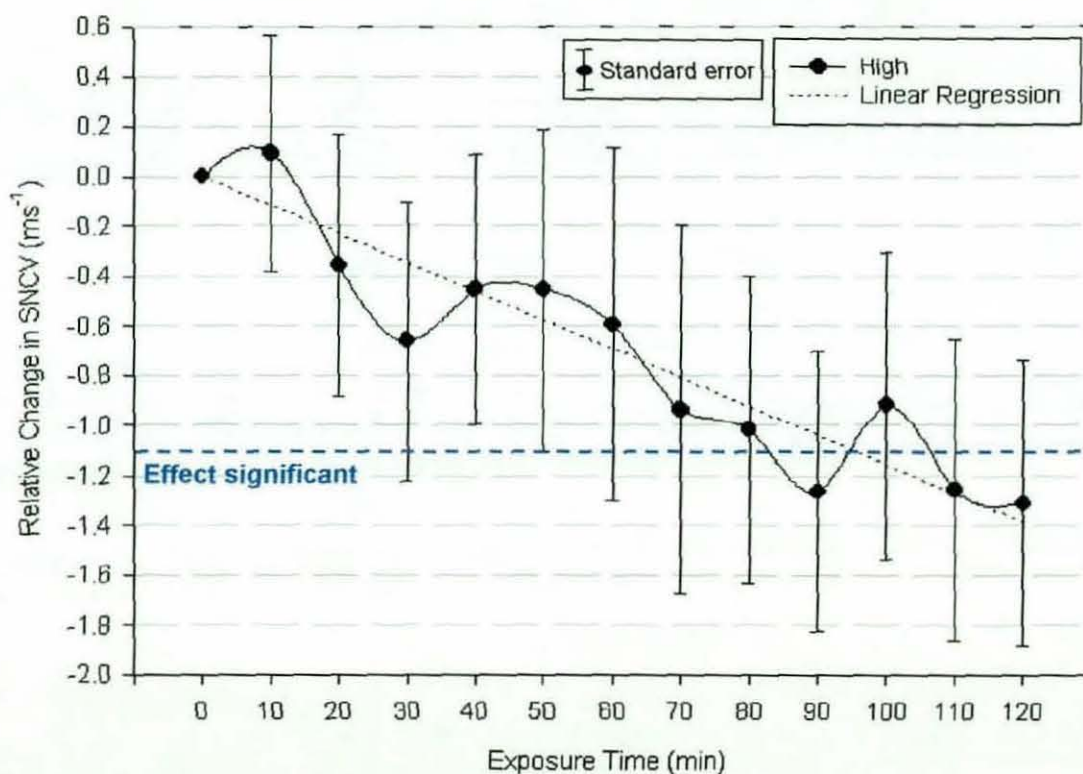
Analysis of Variance involving duration of exposure for within-subject effect (Figure 126) produced the following result (Table 30):

Table 30: ANOVA involving duration of exposure – High

Source of Variation	SS	DF	MS	F	Sig of F	Power
Time	56.77	12	4.73	2.53	0.004	0.973
Within cells	471.97	252	1.87			

Red denotes significance at $\alpha \leq 0.01$ level

A highly significant within-subject effect of duration of exposure (time) was detected across participants. Equation 19 describes the predictive linear function of the effect of duration of exposure on SNCV for the high wrist activity condition.

Equation 19: Predictive function for effect of duration of exposure - High

Expected CV $_{(static)}$ = -(0.012)*Time

$R^2 = 0.024$

Where 'Time' is expressed in minutes of exposure to stressor

F-test analyses resolved for duration of exposure where mean effect across subjects was significantly differentiated ($p<0.05$) from the mean baseline measure (T=0) at T=90 and after T=110 (Figure 126).

Waveform Shift following two-hours uninterrupted exposure to stressors

The mean waveform shift across participants for the high wrist activity condition describes the evoked transformation in temperature-corrected sensory median nerve function (Table 31, Figure 127). The empirical upper limit of normal for sensory peak latency (3.48ms - Jackson and Clifford, 1989) is represented, showing that the effect of duration of exposure, while statistically significant, did not produce electrophysiologic evidence of median nerve neuropathy within 120 minutes of task commencement.

Table 31: Mean waveform descriptors for high activity condition

Measure	Baseline	Induced	% change
Onset Latency (msec)	2.68	2.78	3.72
Peak Latency (msec)	3.30	3.43	3.93
Duration (msec)	0.62	0.63	1.56
Amplitude (μV)	29.59	29.90	1.04
Area (μVmsec)	10.32	11.57	12.14
Conduction Velocity (ms^{-1})	42.79	41.48	-3.07

Figure 127: Mean waveform shift for high activity condition
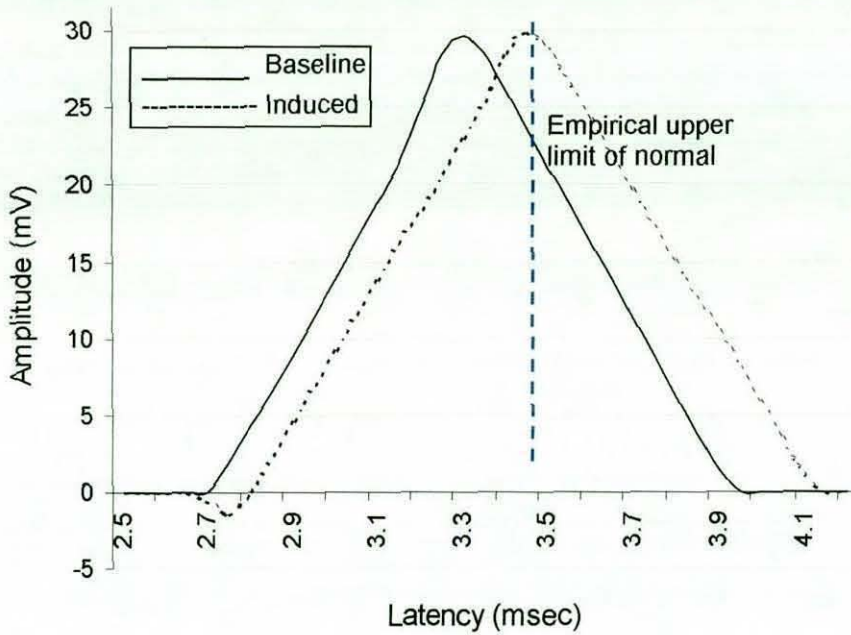
6.5.5 Between Conditions Analysis

Repeated measures analyses of variance were performed to determine whether a significant difference could be detected between wrist activity levels (Figure 121, Table 32).

Table 32: Between conditions repeated measures ANOVA

	Source	SS	DF	MS	F	Sig	Power
Static vs Low (N=9)	Time	45.17	12	3.76	0.96	0.406	0.552
	Within Cells	377.52	96	3.93			
Static vs Medium (N=12)	Time	25.93	12	2.16	0.76	0.518	0.425
	Within Cells	374.93	132	2.84			
Static vs High (N=11)	Time	175.45	12	14.62	2.12	**0.020**	0.923
	Within Cells	826.14	120	6.88			
Low vs Medium (N=19)	Time	14.39	12	1.20	0.93	0.370	0.539
	Within Cells	277.03	216	1.28			
Low vs High (N=11)	Time	103.53	12	8.63	1.56	0.112	0.797
	Within Cells	662.55	120	5.52			
Medium vs High (N=8)	Time	32.31	12	2.69	0.78	0.491	0.417
	Within Cells	290.67	84	3.46			

Blue denotes significance at $\alpha \leq 0.05$ level

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Results indicate a statistically significant difference between the static and high wrist activity conditions. This result signifies effects on nerve conduction uniquely attributable to highly repetitive motion of the wrist.

The Tukey HSD (honest significant difference) test (Equation 20) was utilized to calculate the duration of exposure at which a significant difference between the static and high activity conditions was realized. Tukey HSD is a special form of repeated one-way analysis of variance, which increases the reliability of findings by limiting the degrees of freedom for the sample (Keppel, 1991). Conservative criteria were used throughout this statistical test to enhance confidence in any findings.

Equation 20: Calculation of critical difference for Tukey HSD test

Critical difference (CD) for $\alpha = 0.05$; $r = 13$; $df = \infty$; $\Rightarrow q = 4.68$

Where: α denotes significance level of test

r = total number of comparisons

df = degrees of freedom

q= Studentized range statistic, derived from the normal distribution and is an adjustment for the number of means being compared.

$$CD = q\sqrt{\frac{MS_{within}}{n_{harmonic}}}$$

$$MS_{within} = \left(\frac{\sum MS_{within}events}{n_{events}}\right) = \left(\frac{\sum 1.17 + 0.59 + 0.41 + 1.87}{4}\right) = 1.01$$

$$n_{harmonic} = \frac{a}{\sum 1/n_{events}} = \frac{4}{\sum\left(\frac{1}{38} + \frac{1}{19} + \frac{1}{40} + \frac{1}{22}\right)} = 26.77$$

$$\Rightarrow CriticalDifference_{0.05} = 0.909ms^{-1}$$

Using previously defined linear predictive functions of SNCV for the static and high wrist activity conditions (Equations 18 and 19, respectively), revealed that the two conditions differed significantly after 52 minutes of continuous exposure.

6.6 Wrist Activity Analysis

Analyses were performed to ascertain which measure of wrist activity presents the strongest definition as to the causal effect of induced physical stressors on temperature-corrected sensory median nerve conduction velocity.

6.6.1 Correlations between Wrist Activity and SNCV

Correlation analyses were performed between measures of wrist activity and temperature-adjusted sensory median nerve conduction velocity across participants and conditions (N=81) using the Pearson's two-tailed technique. The following results were attained (Table 33).

Table 33: <u>Correlations between wrist activity measures and SNCV</u>

Measure of Wrist Activity		FE	RU	PS	Combined
Cycle Time	Pearson Correlation	0.210	0.191	0.167	0.210
	Sig. (2-tailed)	0.060	0.087	0.137	0.060
Mean Positive Displacement	Pearson Correlation	0.080	-0.148	0.022	0.052
	Sig. (2-tailed)	0.476	0.188	0.843	0.644
Peak Positive Displacement	Pearson Correlation	0.141	-0.255	-0.060	0.024
	Sig. (2-tailed)	0.209	0.022	0.592	0.835
Mean Negative Displacement	Pearson Correlation	-0.139	0.087	0.062	-0.136
	Sig. (2-tailed)	0.215	0.453	0.582	0.225
Peak Negative Displacement	Pearson Correlation	-0.075	0.043	0.045	-0.085
	Sig. (2-tailed)	0.504	0.711	0.693	0.450
Mean Range of Motion	Pearson Correlation	-0.034	-0.145	0.045	-0.054
	Sig. (2-tailed)	0.760	0.195	0.692	0.631
Peak Range of Motion	Pearson Correlation	0.043	-0.221	-0.006	-0.049
	Sig. (2-tailed)	0.706	0.047	0.959	0.664

Table 33: <u>Correlations between wrist activity measures and SNCV</u> (continued)

Measure of Wrist Activity		FE	RU	PS	Combined
Mean Angular Velocity	Pearson Correlation	-0.274	-0.308	0.016	-0.282
	Sig. (2-tailed)	0.013	0.005	0.888	0.011
Peak Angular Velocity	Pearson Correlation	-0.265	-0.313	-0.050	-0.288
	Sig. (2-tailed)	0.017	0.004	0.658	0.009
Mean Angular Acceleration	Pearson Correlation	-0.312	**-0.363**	-0.033	**-0.318**
	Sig. (2-tailed)	0.005	**0.001**	0.772	**0.004**
Peak Angular Acceleration	Pearson Correlation	-0.306	-0.306	-0.089	-0.317
	Sig. (2-tailed)	0.005	0.006	0.430	0.004
Force	Pearson Correlation	-0.278	-0.318	-0.088	-0.292
	Sig. (2-tailed)	0.012	0.004	0.437	0.008
Work	Pearson Correlation	-0.143	-0.262	0.027	-0.147
	Sig. (2-tailed)	0.202	0.018	0.812	0.190

Blue denotes significance at $\alpha \leq 0.05$ level
Red denotes significance at $\alpha \leq 0.01$ level

Several kinematic measures of wrist motion, including mean and peak angular velocity, mean and peak angular acceleration, force and work presented significant results. Mean angular acceleration in the radial-ulnar plane of wrist motion presents the strongest correlation with temperature corrected SNCV (R=-0.363, p=0.001), where SNCV decreases as mean angular acceleration increases. Mean correlation across planes of wrist motion was greatest for mean angular acceleration.

6.6.2 Regression analysis for Mean Angular Acceleration and SNCV

Given the highly significant association between RMS mean angular acceleration and temperature corrected sensory median nerve conduction velocity, effect sizes were further explored using non-linear regression analysis (Figure 128, Table 34, and Equation 21).

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Figure 128: <u>Non-linear regression for mean angular acceleration & SNCV</u>
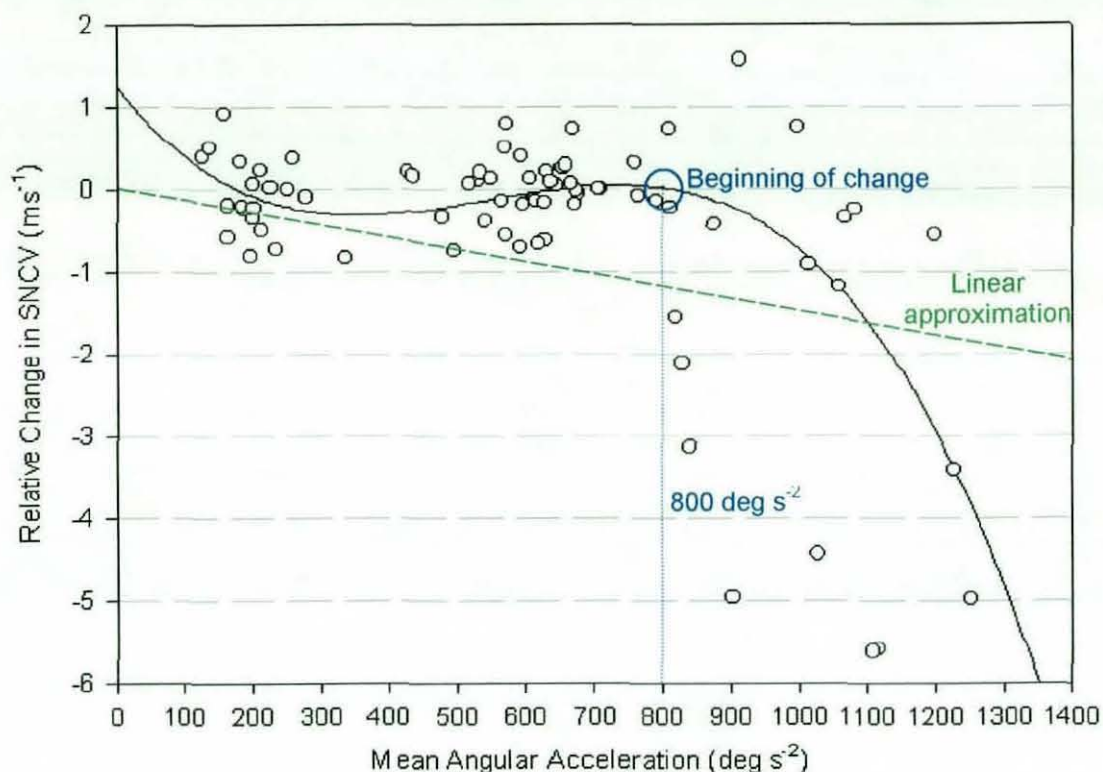
The function which best describes the effect of mean angular acceleration on temperature-adjusted sensory nerve conduction velocity is cubic (Figure 128, Equation 21). SNCV remains relatively unchanged until imposed physical stressors, described as mean angular acceleration of the wrist, achieves a threshold of approximately 800 deg s^{-2}, following which there is a progressive decline in the response of the median nerve.

Table 34: <u>Non-linear regression analysis of mean acceleration and SNCV</u>

Model	Unstandardized coefficients		Standardized coefficients		
	B	Standard error	Beta	T	p
Constant	42.367	1.230		34.438	**<0.001**
Mean accel	$-1.04e^{-2}$	0.008	-1.968	-1.323	0.190
Mean accel^2	$2.18e^{-5}$	$1.36e^{-5}$	5.378	1.599	0.114
Mean accel^3	$-1.34e^{-8}$	$6.82e^{-9}$	-3.901		

Red denotes significance at $\alpha \leq 0.01$ level

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Equation 21: Effect of mean angular acceleration on SNCV

$$SNCV = 42.367 - 0.0104*(ma) + 2.18e^{-5}*(ma^2) - 1.34e^{-8}*(ma^3)$$
$$R = 0.461, \; p=0.0004$$

Where: ma = RMS mean angular acceleration across planes of wrist motion

Linear approximation of the effect of RMS mean angular acceleration on temperature-adjusted sensory median nerve conduction velocity across participants and conditions (Figure 128) describes a **0.0015 ms^{-1}** decrease in SNCV by for each **1.0 deg s^{-2}** increase in mean angular acceleration.

6.6.3 SNCV as a function of Work and Duration of Exposure

The following figure illustrates the change in sensory nerve conduction performance as a function of magnitude and duration of exposure to work (Figure 129).

Figure 129: Relative change in SNCV as a function of work and exposure
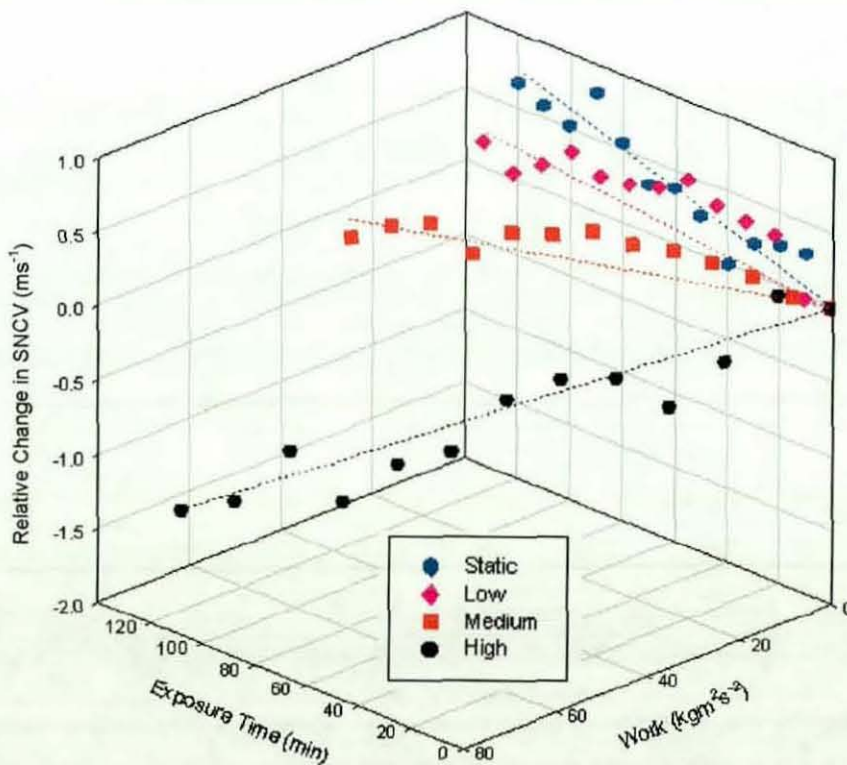
Work was calculated as the product of hand mass, mean acceleration and (linear) distance through which the hand was moved. After two-hours exposure to the low, medium, and high wrist activity levels, mean work performed across participants was 30, 137 and 218 kgm^2s^{-2}, respectively. Presented as a function of work performed and duration of exposure, the effect of wrist activity on median nerve function was found to be significantly (p=0.004) detrimental for the high activity condition.

6.7 Subjective Comfort Rating

A self-reporting tool could be a cost-effective and time-efficient alternative to electroneurometry for workplace surveillance. Subjective measures of perceived upper extremity comfort were evaluated as a possible approximation to objective measures of sensory nerve conduction velocity.

6.7.1 Correlations between SNCV and Subjective Comfort

Correlation analyses were performed using the Pearson's method between subjective comfort rating (Figures 93-96) and temperature-corrected sensory nerve conduction velocity (Figure 121). Results are presented across participants for each condition and across all conditions (Table 35).

Table 35: <u>Correlations between SNCV and subjective comfort rating</u>

	Static	Low	Medium	High	Overall
Pearson Correlation	-0.084	0.200	-0.042	0.138	0.109
Sig. (2-tailed)	0.616	0.413	0.797	0.539	0.237
N	38	19	40	22	119

Correlation analyses between objective and subjective measures did not identify any significant associations. Perceived comfort presents a poor and statistically unqualified approximation to temperature-adjusted sensory median nerve conduction velocity.

6.8 Personal Characteristics

Cited literature suggests that changes in sensory median nerve performance may, in part, be explained by personal risk factors. Covariate effects of participant demographics, subject anthropometry and medical results, on temperature-adjusted sensory nerve conduction velocity were explored.

6.8.1 Correlations between Demographic Variables and SNCV

Pearson's correlation analyses were performed between demographic variables and temperature-corrected sensory median nerve conduction velocity, across participants and conditions (N=97). The variable of gender did not present opportunity for evaluation, since all participants were female. The following results were attained (Table 36).

Table 36: <u>Correlations between participant demographics and SNCV</u>

Demographic Measure	Pearson Correlation	Sig. (2-tailed)
Age	0.049	0.598
Race	-0.020	0.830
Dominant Hand	0.149	0.106
Physical Limitations	0.028	0.760
Smoking History	0.035	0.706
Menstrual Cycle - Static	0.162	0.353
Menstrual Cycle - Low/Medium	-0.293	**0.029**
Menstrual Cycle - High	0.171	0.458

Blue denotes significance at $\alpha \leq 0.05$ level

A small though significant association was detected between sensory conduction velocity and menstrual cycle for the low/medium groups (R^2=-0.086, p=0.029), where SNCV appears to decrease as the number of days since the last menstrual cycle increases (refer to Appendix 4, Table 7). Age (R=0.049, p=0.598), race (R=-0.020, p=0.830) and smoking history (R=0.035, p=0.706) did not present significant associations with SNCV.

6.8.2 Correlations between Anthropometric Measures and SNCV

Correlation analyses were performed using the Pearson's technique between subject anthropometric measures and temperature-adjusted sensory median nerve conduction velocity, across participants and conditions (N=97). The following results were attained (Table 37):

Table 37: <u>Correlations between subject anthropometry and SNCV</u>

Anthropometric Measure	Pearson Correlation	Sig. (2-tailed)
Weight	-0.043	0.643
Stature	0.074	0.423
Body Mass Index	-0.062	0.505
Hand Length	0.216	**0.019**
Hand Breadth	0.120	0.192
Hand Thickness	-0.101	0.275
Hand Mass	-0.043	0.643
Palm Length	0.179	0.051
Thumb Length	0.092	0.321
Index Finger Length	0.145	0.115
Middle Finger Length	0.210	**0.022**
Wrist Breadth	0.021	0.819
Wrist Depth	-0.020	0.828
Wrist Ratio	0.054	0.561
Hand Volume	0.189	**0.040**
Skin Fat	-0.068	0.460
Dominant Power Grip	-0.007	0.939
Non-Dominant Power Grip	0.127	0.168
Dominant Pinch Grip	-0.031	0.734
Non-Dominant Pinch Grip	0.075	0.418

Blue denotes significance at $\alpha \leq 0.05$ level

Small, though significant correlations were discovered between SNCV and anthropometric measures of hand length, middle finger length and hand volume. In contrast to the cited literature, neither body mass index nor wrist ratio was found to be significantly associated with SNCV for this population.

6.8.3 Correlations between Medical Results and SNCV

Correlation analyses were performed between participant medical results and temperature-corrected sensory median nerve conduction velocity, using the Pearson's two-tailed technique, across participants and conditions (N=119). No significant correlations were discovered (Table 38).

Table 38: <u>Correlations between medical results and SNCV</u>

Medical Results	Pearson Correlation	Sig. (2-tailed)
Previous CTS Diagnosis	-0.020	0.830
Family History	-0.095	0.304
X-Ray Findings	-0.111	0.228
Skin Changes	0.154	0.095
Sed Rate	-0.058	0.536
White Cell Count	0.033	0.724
Red Cell Count	0.062	0.505
Hemoglobin	0.166	0.071
Hematrocrit	0.143	0.120
MCV	0.084	0.365
MCH	0.082	0.373
MCHC	0.029	0.752
RDW	-0.161	0.081
Platelet Count	-0.071	0.443
Absolute Neutrophils	0.042	0.646
Neutrophils	0.059	0.522
Absolute Lymphocytes	-0.003	0.978
Lymphocytes	-0.054	0.562
Absolute Monocytes	-0.109	0.236
Monocytes	-0.152	0.099
Absolute Eosinophils	0.136	0.160
Eosinophils	0.054	0.556
Absolute Basophils	-0.160	0.082
Basophils	-0.065	0.484

CHAPTER 7: INTERPRETATION AND DISCUSSION

This chapter presents points for discussion. A summary and interpretation of key findings is offered. Considerations as to the limitations of the methodology and usefulness of the results are discussed. Findings are compared and contrasted with other studies and placed within the context of existing knowledge.

7.1 Summary of Key Findings

One-way analyses of variance were performed across each objective measure of sensory median nerve function (onset latency, peak latency, duration, amplitude, area and conduction velocity) against duration of exposure for each condition. Eta-square (effect size) values were calculated and summed across the matrix (Table 13). Nerve conduction velocity (peak latency divided by nerve length) was found to be the most sensitive measure of sensory median nerve function $(\eta^2=0.429)$. Sensory nerve conduction velocity (SNCV) was thus used throughout subsequent analyses as the major measure of sensory nerve function.

Measures of near-nerve skin temperature (NNST) were found to be significantly correlated with sensory nerve conduction velocity, where SNCV decreased as NNST decreased (Table 16). Fingertip measures of NNST presented the strongest correlation (R=0.747, p<0.001). Using analysis of covariance, the effect of near-nerve skin temperature on SNCV was statistically removed, producing a temperature-adjusted residual of sensory nerve conduction velocity.

After adjusting for changes in near-nerve skin temperature, a significant within-subject effect of duration of exposure (time) was detected using ANOVA for the static (p=0.032) and high (p=0.004) activity conditions (Figures 122 and 126). Adjusted sensory median nerve responses for the low and medium activity levels were statistically undifferentiated in comparison to their respective baseline measures (time=0). Using the F-test, a significant

(p<0.05) change in median sensory nerve conduction velocity was first distinguishable after 90 minutes of exposure. For 40.2 meters per second as the empirical lower limit of normal for sensory median nerve conduction velocity, the predicted duration required to generate abnormally low SNCV for the high wrist activity level was 224 minutes; well within the scope of a typical workday.

A between-groups repeated measures analysis of variance was performed, which found that temperature-adjusted measures of sensory nerve conduction velocity differed significantly (p=0.020) between the static and high activity conditions (Figure 121, Table 32). This finding signifies effects on nerve conduction that are uniquely attributable to highly repetitive hand motion. For a critical difference of $0.91 ms^{-1}$, calculated using the Tukey test, a significant difference between these conditions was realized after 52 minutes of continuous exposure. After 120 minutes of exposure, the difference was $2.1 ms^{-1}$.

Several kinematic measures of wrist motion, including mean and peak angular velocity, mean and peak angular acceleration, force and work presented significant correlations with SNCV (Table 33). Mean angular acceleration in the radial-ulnar plane of wrist motion presents the strongest correlation (R=-0.363, p=0.001), where temperature-adjusted SNCV decreases as mean angular acceleration increases. Across planes of wrist motion, the strongest correlate was also mean angular acceleration. The function that best describes the effect of mean angular acceleration on temperature-adjusted sensory nerve conduction velocity is cubic (Figure 128). SNCV remains relatively unchanged until imposed physical stressors, described in terms of mean angular acceleration of the wrist, achieves a threshold of approximately $800 \deg s^{-2}$, following which there is a progressive decline in the response of the median nerve. Linear approximation to this effect describes a $0.0015 ms^{-1}$ decrease in SNCV by for each $1.0 \deg s^{-2}$ increase in mean angular acceleration.

Work was calculated as the product of hand mass, mean acceleration and (linear) distance through which the hand was moved. After two-hours exposure to the low, medium, and high wrist activity levels, mean work performed across all participants was 30, 137 and $218 \ kgm^2 s^{-2}$, respectively.

Presented as a function of work performed and duration of exposure, the effect of wrist activity on median nerve function was found to be significantly (p=0.004) detrimental for the high wrist activity condition (Figure 129).

Approximately one half of all subjects professed symptoms that were suggestive of carpal tunnel syndrome during task performance. Symptoms included numbness, tingling and perception of coldness across the median distribution of the hand. Sensory nerve conduction velocities returned to initial baseline levels in all subjects by the following day. Correlation analyses between objective and subjective measures did not identify any significant associations. Perceived comfort, therefore, presents a poor and statistically unqualified approximation to temperature-adjusted sensory median nerve conduction velocity.

7.2 Observations in Unadjusted Electroneurologic Measures

Observations during the course of this study pertaining to raw measures of nerve performance (i.e. unadjusted for near-nerve skin temperature) help to explain several previously documented phenomena.

7.2.1 Workday Effect

Across all conditions, the largest within-subject change in unadjusted sensory nerve conduction velocity (SNCV) occurred during the first 2-hour session of the day (Figures 89-92). During the first session, unadjusted SNCV decreased incrementally approaching empirical lower limits of normal. In some cases, a temporary threshold shift in nerve conduction was produced consistent with electrophysiologic evidence of carpal tunnel syndrome. A further noticeable decrease followed the morning break. The second 2-hour session exhibited recovery during the first part, followed by slowing, resulting in little overall effect of the session. There was a further decrease in nerve conduction during the lunch period, following which SNCV recovered quickly

then leveled off. The overall effect of the workday was negligible from start to end, but with significant variability between the ends.

The observed overall effect of the workday is consistent with the findings of a doctoral field study presented by Bartol in 1995, in which pre and post workshift electrophysiological measures were statistically undifferentiated across a group of asymptomatic workers.

7.2.2 Initial Increase in Sensory Nerve Performance

There appears to be an initial, though statistically insignificant ($p>0.05$), increase in unadjusted nerve conduction velocity during the first thirty minutes of activity during session 1 (mean effect size across participants and conditions = 1.4%) (Figures 89-92). This effect coincides with an initial increase in near-nerve skin temperatures across the median distribution of the hand (Figures 98-109). The observed effect was obvious across participants and conditions and therefore not due to outlier data.

Considering the proposed speculative etiological mechanism for CTS (Figure 23), deterioration of axonal flow in the nerve fibers is thought to be due to inhibited microcirculation brought about by increased pressures within the carpal tunnel (Kerwin et al, 1996). When enhanced nerve performance is observed, the opposite should be true. That is, axonal flow may be encouraged by improved microcirculation resulting from decreased interstitial pressures. Onset of activity might cause an increase in blood flow to the extremity due to a pumping action associated with muscular demands of the task. Enhanced vascular function would explain the increase in near-nerve skin temperature.

Seradge et al (1995) observed a similar phenomenon across both control and patient populations where measured intra-tunnel pressures dropped after one minute of hand and wrist exercises. The investigators noted that pressures remained below normal during fifteen minutes of continuous measurement. Consistent with the above report, unadjusted measures of median nerve conduction in this study returned to normal within 20-30

minutes of onset of activity and continued to deteriorate thereafter (Figures 89-92).

Adequate vascular supply of the median nerve may be dependent upon moderate motion. The offered explanation may in part explain the nocturnal exacerbation of symptoms in CTS patients. Moderate wrist motion would seem to foster improved circulation, thereby promoting neurophysiological recovery.

This finding might explain the positive findings of aggressive rehabilitation programs for CTS patients (Goodman, 1992). It is proposed that brief intermittent and moderate hand and wrist exercises may produce temporary relief from mild symptoms of the syndrome.

7.2.3 Nerve Conduction Characteristics following Task Break

It is thought that the observed reduction in unadjusted sensory nerve conduction velocity observed following break periods (Figures 89-92) may be due to cessation of wrist motions during the break causing a decrease in activity promoted blood circulation. Thus, axonal transport rate may have decreased due to diminished metabolic efficiency of the median nerve. This theory is supported by the concurrent decrease in near-nerve skin temperature (Figures 98-109) following break periods.

7.3 Interpretation of Results

Results presented herein describe a dose-response relationship between wrist activity and temperature-adjusted sensory median nerve function, where nerve conduction velocity decreases according to a cubic function as mean angular acceleration of the wrist increases. Mean angular acceleration is a somewhat meaningless kinematic variable beyond the scientific community and offers little direct opportunity for practical application. A following discussion is offered, which presents a simpler measure that may be more readily interpreted in the workplace.

A three-dimensional biomechanical model of tendon forces at the wrist is offered to explain the potential contributory effects of physical risk factors on tendon forces at the wrist. Safe wrist-workload exposure limits are expressed using this model, allowing estimation of the effects of individual and combined physical risk factors. This model offers a method by which findings of the study can be employed for workplace exposure surveillance and the development of ergonomic recommendations for workstation design.

7.3.1 Estimation of Exposure Limits for Wrist Activity

Given an empirical lower limit of normal conduction velocity of $40.2 ms^{-1}$ (Jackson and Clifford, 1989) and based on Equation 21, mean angular accelerations of the wrist greater than $1,022$ deg s^{-2} may impede sensory median nerve function such that clinical evidence of carpal tunnel syndrome is evoked (Figure 130).

Figure 130: <u>Non-linear regression for mean angular acceleration & SNCV</u>
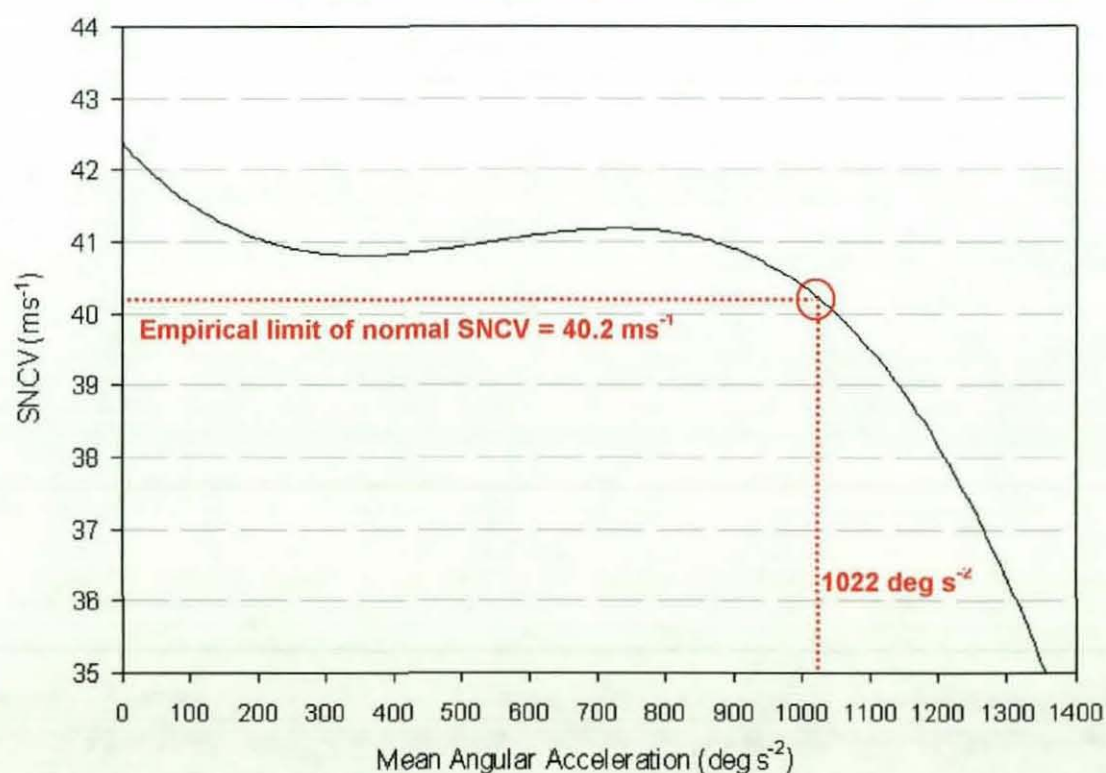
For practical purposes, safe wrist-workload exposure limits (SWELs) could be expressed as a function of task frequency. Wrist activity data across participants and conditions was used to determine cycle time (CT) as a function of mean angular acceleration (Table 39, Figure 131, Equation 22). The two measures correlate highly across conditions (R^2=0.803, p<0.001).

Table 39: <u>Regression analysis of mean angular acceleration & cycle time</u>

Model	Unstandardized coefficients		Standardize coefficients		Correlations	
	B	Standard error	Beta	p	Zero-order	Semi partial
Constant	2.462	0.058		<0.001		
Mean accel	-1.52e^{-3}	0.000	-0.569	<0.001	-0.896	-0.896

Red denotes significance at α<0.01 level

Figure 131: <u>Cycle time as a function of mean angular acceleration</u>

Task Frequency = 0.909cycles per second

1022 deg s^{-2}

Mean Angular Acceleration (deg s^{-2})
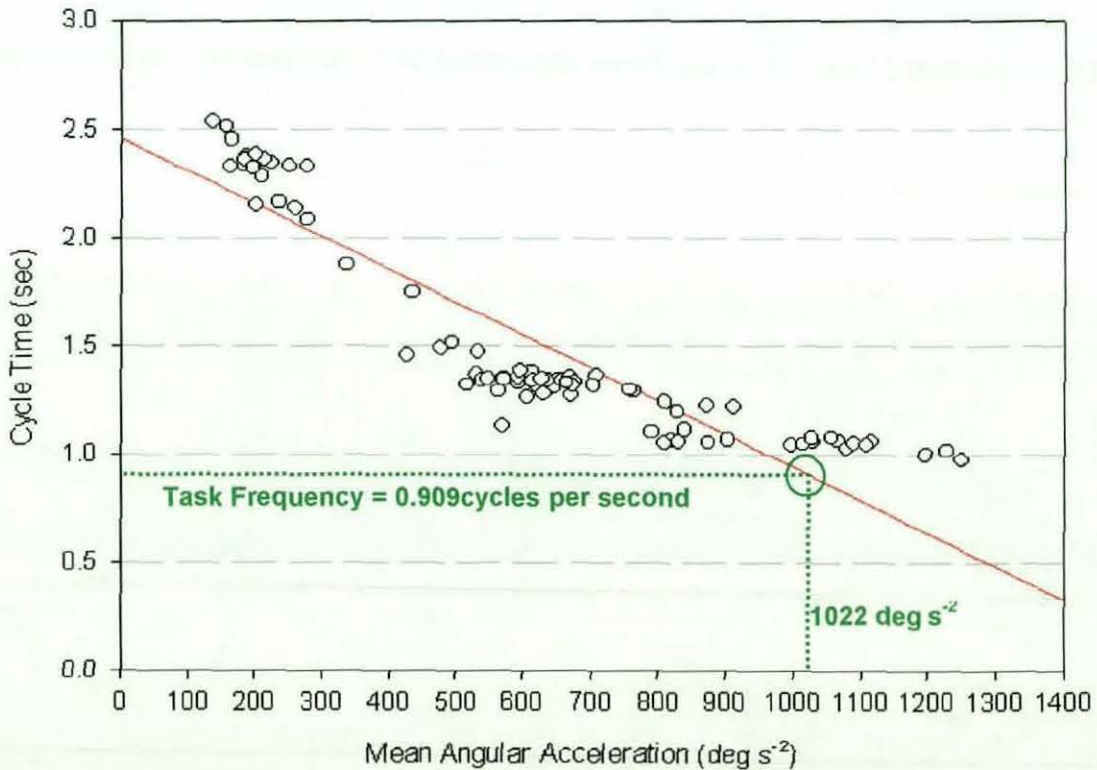
Equation 22: <u>Safe exposure limits as a function of task frequency</u>

$$CT = 2.462 - 1.52e^{-3} \times meanangularacceleration$$

$$= 2.462 - \frac{meanangularacceleration}{656.51}$$

$$TaskFreq_{RPM)} = 60 \times \frac{1}{CT}$$

$$\therefore SWEL_{RPM} = \frac{60}{2.462 - \left(meanangularacceleration \Big/ 656.51 \right)}$$

Safe wrist-workload exposure limits may therefore be expressed as a function of task repetition rate, with reasonable confidence. Solving for the defined empirical upper limit of 1,022 deg s^{-2} confers that SWEL$_{(RPM)}$= 66.04, or 0.91 seconds per task cycle (Figure 131).

The above safe wrist-workload exposure limit was derived for an unloaded hand, where the only load acting on the biomechanical wrist system was due to the mass of the hand (sample mean = 0.34 kg). Furthermore, this limit was established considering two hours of constant exposure.

7.3.2 Biomechanical Model of Tendon Forces at the Wrist

A biomechanical model (Figure 132, Equation 23) was developed to summarize the basic concepts offered in the previously cited literature.

The model assumes the metacarpal joints to be fixed in a neutral posture. Biomechanical forces generated by grasping actions are thus unexplained.

The model is an example of how biomechanical modeling can facilitate in the evaluation of the contributory effects of individual and combined physical risk factors. Safe exposure limits for work-related upper extremity musculoskeletal disorders may be developed based on such models, which would be valuable for workplace hazard surveillance and the establishment of ergonomic recommendations for workstation design.

7.3.2.1 Model Logic

For the wrist system to be in balance under static or dynamic conditions, the sum of all moments acting about the wrist must be zero. A free body diagram is used to explain the sum of static moments by its elements. Dynamic moments are similarly expressed using a mass-acceleration diagram. Total forces acting on the tendons at the wrist are thus presented according to their static and dynamic components.

Figure 132: <u>A simple biomechanical model of tendon forces at the wrist based on the literature</u>
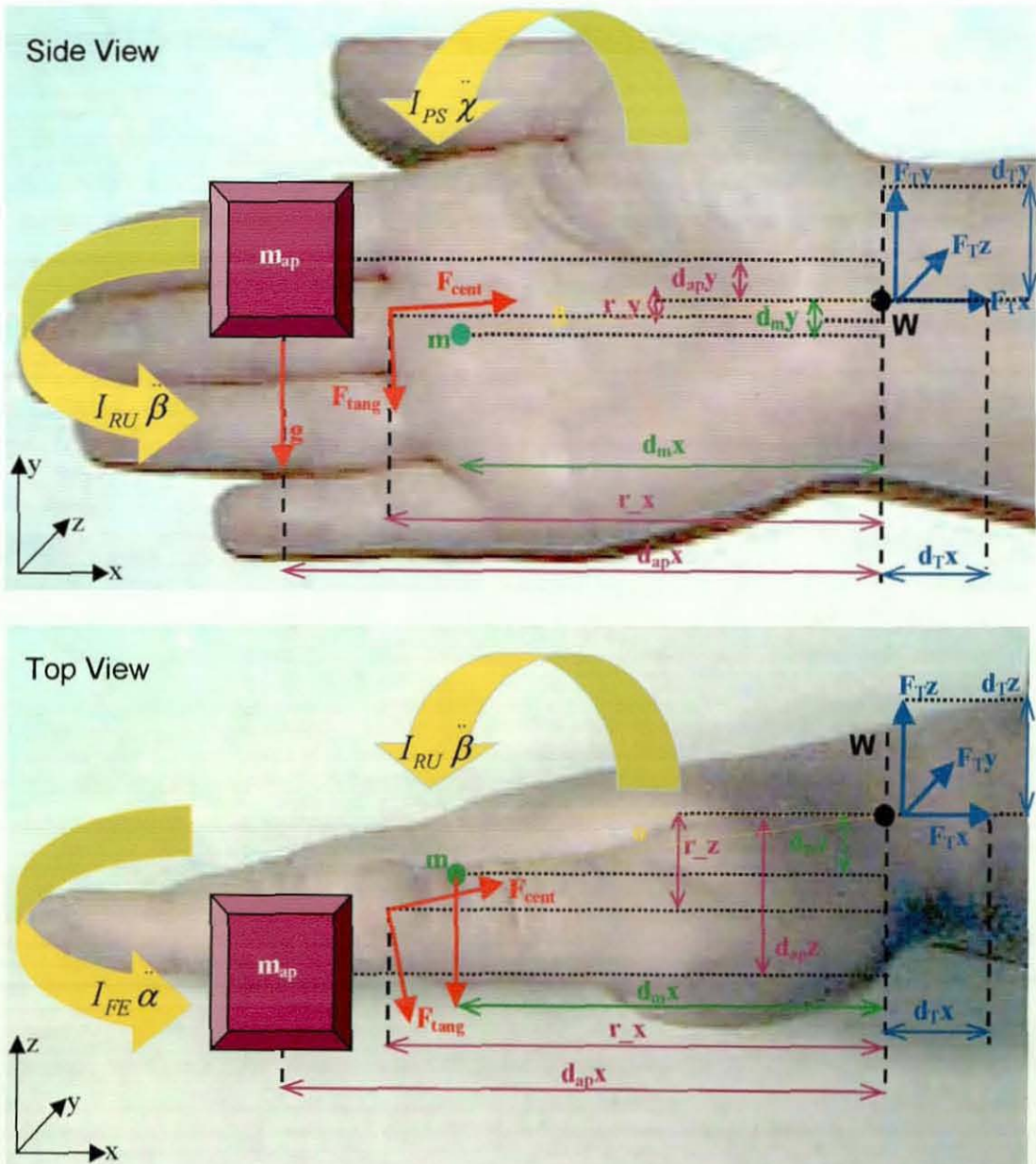
Key

W = wrist action point

m = mass of hand
m_{ap} = mass of external applied load

g = gravitational acceleration
F_{cent} = centrifugal forces
F_{tang} = tangential forces

$F_T x$ = force acting on tendon (x-axis)
$F_T y$ = force acting on tendon (y-axis)
$F_T z$ = force acting on tendon (z-axis)

$d_T x$ = distance traveled by tendon (x-axis)
$d_T y$ = distance traveled by tendon (y-axis)
$d_T z$ = distance traveled by tendon (z-axis)

$d_m x$ = distance from center of mass of hand to wrist action point (x-axis)
$d_m y$ = distance from center of mass of hand to wrist action point (y-axis)
$d_m z$ = distance from center of mass of hand to wrist action point (z-axis)

$d_{ap} x$ = distance from center of applied load to wrist action point (x-axis)
$d_{ap} x$ = distance from center of applied load to wrist action point (x-axis)
$d_{ap} x$ = distance from center of applied load to wrist action point (x-axis)

r_x = distance between force action center to wrist action point (x-axis)
r_y = distance between force action center to wrist action point (y-axis)
r_z = distance between force action center to wrist action point (y-axis)

I_{FE} = inertial forces (flexion-extension plane)
I_{RU} = inertial forces (radial-ulnar plane)
I_{PS} = inertial forces (pronation-supination plane)

α = angular displacement (flexion-extension plane) in radians
β = angular displacement (radial-ulnar plane) in radians
χ = angular displacement (pronation-supination plane) in radians
θ = combined angular displacement in radians

$\ddot{\alpha}$ = angular acceleration (flexion-extension plane) in radians / sec^2
$\ddot{\beta}$ = angular acceleration (radial-ulnar plane) in radians / sec^2
$\ddot{\chi}$ = angular acceleration (pronation-supination plane) in radians / sec^2
$\ddot{\theta}$ = combined angular acceleration in radians / sec^2

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Equation 23: A simple biomechanical model of tendon forces at the wrist

Static Model	Dynamic Model
(Free Body Diagram)	(Mass x Acceleration Diagram)

$$\sum M_W (FBD) \equiv \sum M_W (MAD)$$

Static Model (Free Body Diagram)	Dynamic Model (Mass x Acceleration Diagram)
$\sum M_W (FBD) = M_T - M_m - M_{ap} = 0$	$\sum M_W (MAD) = M_{cent} + M_{\tan g} + I.\ddot{\theta} = 0$
$M_T = M_m + M_{ap}$	$M_{cent} = F_{cent}.r$
$F_T.d_T = F_m.d_m + F_{ap}.d_{ap}$	$where ....F_{cent} = m_{cent}.a_{cent}$
$F_T.d_T = m.g.d_m + m_{ap}.g.d_{ap}$	$r = \dfrac{d_m + d_{ap}}{2}$
$\Rightarrow \sum M_W (FBD) = F_T.d_T - g(m.d_m + m_{ap}.d_{ap})$	$m_{cent} = m + m_{ap}$
	$a_{cent} = \dfrac{v_{cent}^{\ 2}}{r} = \left(\dfrac{r.\dot{\theta}_1}{r}\right)^2$
	$\therefore M_{cent} = \left(m + m_{ap}\right)\ddot{\theta}_1.\left(\dfrac{d_m + d_{ap}}{2}\right)$
	$similarly$
	$M_{\tan g} = \left(m + m_{ap}\right)\ddot{\theta}_2.\left(\dfrac{d_m + d_{ap}}{2}\right)$
	$\Rightarrow \sum M_W (MAD)$
	$= \left(m + m_{ap}\right)\left(\dfrac{d_m + d_{ap}}{2}\right).(\ddot{\theta}_1 + \ddot{\theta}_2) + I.\ddot{\theta}$

$$F_T.d_T - g(m.d_m + m_{ap}.d_{ap}) = \left(m + m_{ap}\right)\left(\frac{d_m + d_{ap}}{2}\right).(\ddot{\theta}_1 + \ddot{\theta}_2) + I.\ddot{\theta}$$

$$F_T.d_T = g(m.d_m + m_{ap}.d_{ap}) + \left(m + m_{ap}\right)\left(\frac{d_m + d_{ap}}{2}\right).(\ddot{\theta}_1 + \ddot{\theta}_2) + I.\ddot{\theta}$$

$$F_T = \frac{g(m.d_m + m_{ap}.d_{ap}) + \left(m + m_{ap}\right)\left(\dfrac{d_m + d_{ap}}{2}\right).(\ddot{\theta}_1 + \ddot{\theta}_2) + I.\ddot{\theta}}{d_T}$$

static	dynamic

Flexion-Extension

$$F_T x = \frac{M_m x + M_{ap} x + M_{cent} + I_{FE} . \ddot{\alpha}}{d_T x}$$

$$M_m x = m.g.(1 - (\sin \beta + \sin \chi)).d_m x$$

$$M_{ap} x = m_{ap} .g.(1 - (\sin \beta + \sin \chi)).d_{ap} x$$

$$M_{cent} = (m + m_{ap})[\arcsin(\sin \beta + \sin \chi)]^2 . \left(\frac{d_m x + d_{ap} x}{2} \right)$$

$$\therefore F_T x = \frac{(m.d_m x + m_{ap} .d_{ap} x).g.(1 - (\sin \beta + \sin \chi)) + (m + m_{ap})\left(\frac{d_m x + d_{ap} x}{2} \right).\arcsin(\sin \beta + \sin \chi) + I_{FE} . \ddot{\alpha}}{d_T x}$$

Radial-Ulnar

$$F_T y = \frac{M_m y + M_{ap} y + M_{\tan g} y + I_{RU} . \ddot{\beta}}{d_T y}$$

$$M_m y = m.g.(1 - (\sin \alpha + \sin \chi)).d_m y$$

$$M_{ap} y = m_{ap} .g.(1 - (\sin \alpha + \sin \chi)).d_{ap} y$$

$$M_{\tan g} y = (m + m_{ap})[\arcsin(\sin \alpha + \sin \chi)]^2 . \left(\frac{d_m y + d_{ap} y}{2} \right)$$

$$\therefore F_T y = \frac{(m.d_m y + m_{ap} .d_{ap} y).g.(1 - (\sin \alpha + \sin \chi)) + (m + m_{ap})\left(\frac{d_m y + d_{ap} y}{2} \right).\arcsin(\sin \alpha + \sin \chi) + I_{RU} . \ddot{\beta}}{d_T y}$$

Pronation-Supination

$$F_T z = \frac{M_m z + M_{ap} z + M_{\tan g} z + I_{PS} \cdot \ddot{\chi}}{d_T z}$$

$$M_m z = m.g.(1 - (\sin \alpha + \sin \beta)).d_m z$$

$$M_{ap} z = m_{ap} .g.(1 - (\sin \alpha + \sin \beta)).d_{ap} z$$

$$M_{\tan g} z = \left(m + m_{ap} \right)[\arcsin(\sin \alpha + \sin \beta)]^2 . \left(\frac{d_m z + d_{ap} z}{2} \right)$$

$$\therefore F_T z = \frac{(m.d_m z + m_{ap} .d_{ap} z).g.(1 - (\sin \alpha + \sin \beta)) + \left(m + m_{ap} \right)\left(\frac{d_m z + d_{ap} z}{2} \right).\arcsin(\sin \alpha + \sin \beta) + I_{PS} \cdot \ddot{\chi}}{d_T z}$$

Combined Effect

$$F_T = \sqrt{F_T x^2 + F_T y^2 + F_T z^2}$$

$$\Rightarrow F_T = \begin{cases} \left[\dfrac{(m.d_m x + m_{ap}.d_{ap} x).g.(1-(\sin\beta+\sin\chi)) + \left(m+m_{ap}\right)\left(\dfrac{d_m x + d_{ap} x}{2}\right).\arcsin(\sin\beta+\sin\chi) + I_{FE}.\ddot{\alpha}}{d_T x}\right]^2 \\[2em] + \left[\dfrac{(m.d_m y + m_{ap}.d_{ap} y).g.(1-(\sin\alpha+\sin\chi)) + \left(m+m_{ap}\right)\left(\dfrac{d_m y + d_{ap} y}{2}\right).\arcsin(\sin\alpha+\sin\chi) + I_{RU}.\ddot{\beta}}{d_T y}\right]^2 \\[2em] + \left[\dfrac{(m.d_m z + m_{ap}.d_{ap} z).g.(1-(\sin\alpha+\sin\beta)) + \left(m+m_{ap}\right)\left(\dfrac{d_m z + d_{ap} z}{2}\right).\arcsin(\sin\alpha+\sin\beta) + I_{PS}.\ddot{\chi}}{d_T z}\right]^2 \end{cases}$$

$$\underbrace{\qquad\qquad\qquad}_{\text{static}} \qquad \underbrace{\qquad\qquad\qquad\qquad}_{\text{dynamic}}$$

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7.3.2.2 Wrist Tendon Moments for the Activities Studied

If it were assumed that the mass of the monitoring electrodes applied to the hand is negligible, then the biomechanical model, which describes tendon moments generated at the wrist specific to activities studied, may be simplified as Equation 24.

Equation 24: <u>Calculation of wrist tendon moments for the activities studied</u>

$$\Rightarrow M_T = \sqrt{ \begin{aligned} &\left[(m.d_m x).(g.(1-(\sin\beta+\sin\chi))+\arcsin(\sin\beta+\sin\chi)+I_{FE}.\ddot{\alpha}) \right]^2 \\ &+\left[(m.d_m y).(g.(1-(\sin\alpha+\sin\chi))+\arcsin(\sin\alpha+\sin\chi)+I_{RU}.\ddot{\beta}) \right]^2 \\ &+\left[(m.d_m z).(g.(1-(\sin\alpha+\sin\beta))+\arcsin(\sin\alpha+\sin\beta)+I_{PS}.\ddot{\chi}) \right]^2 \end{aligned} }$$

Static, dynamic and total tendon moment values were calculated for each condition by and across planes of wrist motion (Table 40), where:
- mean hand mass across participants (m) = 0.342 kg
- acceleration due to gravity (g) = 9.82 ms^{-2}

Table 40: <u>Tendon moments at the wrist, by condition and plane of motion</u>

Condition	Plane of Motion	Static Moment	Dynamic Moment	Total Moment
Low	F/E	0.213	0.157	0.370
	R/U	0.022	0.016	0.038
	P/S	0.027	0.020	0.047
	Overall	0.216	0.159	0.375
Medium	F/E	0.211	0.451	0.662
	R/U	0.028	0.059	0.087
	P/S	0.031	0.067	0.098
	Overall	0.216	0.462	0.675
High	F/E	0.208	0.702	0.910
	R/U	0.031	0.103	0.134
	P/S	0.035	0.119	0.154
	Overall	0.214	0.722	0.933

7.3.2.3 Safe Wrist-Workload Exposure Limits

A tendon moment of 0.989 kgm^2 was similarly derived for calculated safe wrist-workload exposure limits of 1,022 deg s^{-2} (Figure 133).

Figure 133: <u>Safe wrist exposure limit as a function of tendon moment</u>
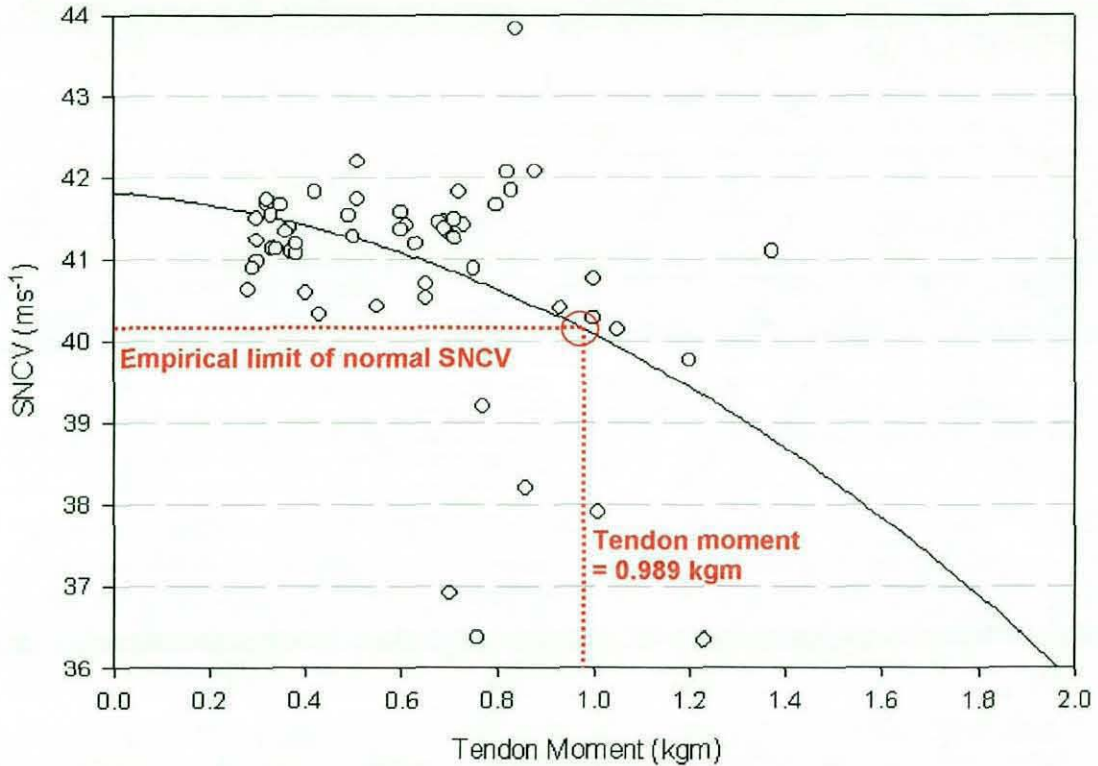
The maximum tendon moment generated by participants during the performance of the high wrist activity in this study was less than the calculated safe exposure limit. Temperature-adjusted SNCV across participants approached empirical limits of normal for this condition.

7.3.2.4 Static and Dynamic Tendon Moments

Static and dynamic elements of Equation 23 facilitate independent evaluation of the effects due to force and repetition. Summing the static and dynamic tendon moments affords an assessment for the overall effect of combinations of risk factors. The ratio of static to dynamic tendon moments provides an overview of the relative contribution of independent risk factors. In this study, no external load was added to the mass of the hand. As task

repetition increased the contribution of dynamic risk factors is seen to exceed static elements (Table 40, Figure 134).

Figure 134: Weighted contribution of static and dynamic tendon moments
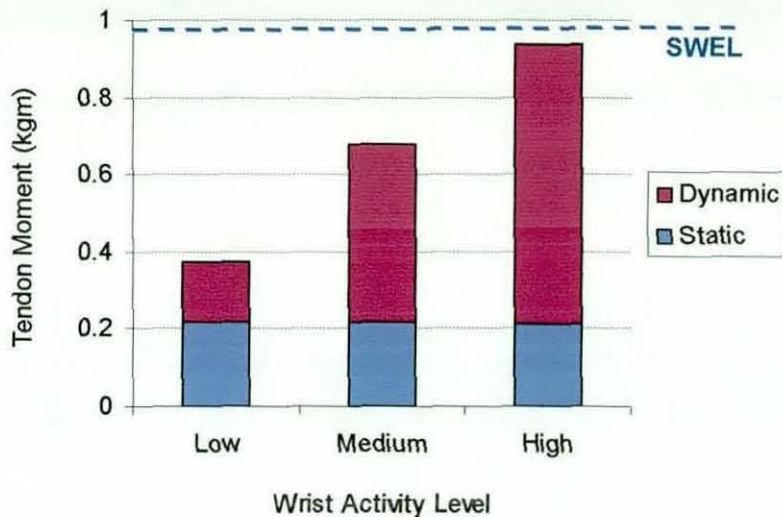
Any variation in hand mass, hand length, application of an external load, location of such load, posture and motion of the wrist may affect tendon moments. The weighted contribution of physical risk factors in Equation 23 appears to be congruent with the previously cited literature.

7.3.2.5 Implications of the Model

Dynamic modeling uses data gathered in the laboratory to predict the forces acting on a joint under different loading conditions. The presented biomechanical model calculates tendon forces at the wrist resulting from imposed physical risk factors. It overcomes limitations of many earlier models by considering both motion and asymmetry of the wrist in calculations of joint loading. The model is unique in that static and dynamic elements of the equation may be used to calculate effects due to force and repetition independently, or summed to assess the overall effect for combinations of risk factors.

The model provides a necessary vehicle for comparing workplace task demands to safe exposure levels, which are proposed on the basis of data from this study. Such a tool would have great value in the workplace, where it

can be utilized for hazard surveillance and the development of ergonomic recommendations for workstation design. However, this model has yet to be validated in field studies.

7.3.2.6 Limitations of the Model

The proposed safe wrist-workload exposure limits were defined for a controlled study population, which may not be indicative of the general working population, and may therefore not be generally applied. Further research is necessary to refine the proposed safe exposure limits across broader population samples and for various task demands. Larger samples should also improve the predictive accuracy of the regression models due to smaller standard deviations of measures.

7.4 Limitations of the Study

Any study is not without limitations. Reasonable effort was given to minimize potential sources of internal, external and construct validity, ensure the reliability and validity of measurement techniques, incorporate sufficiently detailed statistical analyses and avoid logistical issues. If this study were to be repeated, the following adjustments could be considered.

7.4.1 Limitations in the Methodology

During the course of this study, it was realized that selected measurement techniques might have affected the findings presented herein to some degree. Opportunities for methodological adjustments are discussed.

7.4.1.1 Wrist Activity Measures

Due to the complexity of data acquisition, wrist activity measurement was performed hourly, which involved brief cessation of wrist motion while the

electromagnetic tracking system was activated. Furthermore, adequate data storage was an issue due to large file sizes. Infrequent measurement of wrist activity compromised the facility to perform analyses of variance between measures of wrist activity and sensory median nerve function. Future research activities should include provision for wrist activity measures to be acquired as frequently as nerve conduction measures.

This study has confirmed the importance of mean angular acceleration as the kinematic variable that presents the strongest association with median nerve function and risk-potential for the development of work-related upper extremity cumulative trauma disorders, including carpal tunnel syndrome. The technology utilized in this study to monitor wrist activity acquired positional data of the hand with respect to a timeline, from which derivative measures were computed. To minimize the effect of random noise evident within the data, digital signal processing was performed. Depending upon the order of the filter, this process will filter both noise data and overlapping positional data of similar frequencies. It is proposed that future studies incorporate direct measurement of wrist acceleration measures, using accelerometer technology, which will minimize the need for filtering, hence potentially producing a more accurate record of human motion.

7.4.1.2 Electroneurologic Measures

In this study, electroneurologic function of the median nerve was assessed using the antidromic technique, where an evoked sensory response was recorded in the third digit with respect to a proximal stimulus. Peer discussion has suggested that findings presented by this technique may not necessarily be indicative of a pathologic process, but may be representative of a physiologic response of the median nerve fibers.

It is suggested that some of the inferences drawn may gain in credibility if a change in conductivity of the median nerve were not mirrored in the ipsilateral ulnar nerve. Electroneurological comparison of the median and ulnar nerves in the fourth digit might have been appropriate to deduce pathogenesis. However, even this technique is not without limitations. An evaluation of the median-ulnar latency difference technique by Capone et al

(1998) discovered that anatomical variations might compromise the practical usefulness of within-subject findings, where sensory action potential of the respective nerves can be erroneously misinterpreted in as many as twenty percent of cases. Laroy et al (1999) discovered similar complications with this technique in 295 of 2047 hands.

7.4.2 Limitations in the Usefulness of the Results

This study describes a controlled laboratory experiment, in which only healthy asymptomatic female subjects were invited to participate. In the workplace environment, operators might be predisposed to increased prevalence of work-related cumulative trauma disorders due to confounding medical conditions and other personal risk factors. Furthermore, multiple physical risk factors are typically evident in many hand-intensive operations.

7.4.2.1 Sample Limitations

The population sample that participated in this study was carefully controlled to minimize confounding variables. As such, findings presented herein, including proposed threshold limits, may not be generally applicable.

The literature indicates a higher prevalence of carpal tunnel syndrome among female populations, therefore, males may not be as sensitive to presented physical stressors. The effect of race on nerve conduction is not clearly known, though it is suspected based on epidemiological findings that recorded effects may not be as considerable for non-white populations. Presence of confounding medical conditions would likely increase individual susceptibility to effects of imposed stressors. Implications of such effects should be considered if findings are to be applied across broad populations.

Findings of this study offer quantification for several previously theorized or inadequately substantiated associations, for which sample control was justified. Opportunities for future research activities arising from this study should involve broader samples, including males, non-whites and symptomatic populations.

7.5 Place in Context of Existing Knowledge

The study reported in this thesis examined wrist activities characteristic of low, medium and high-risk repetitious activities with comparison to a static task. Previous reports have demonstrated an increased incidence in CTS not only with static hand positioning and repetitive wrist movements but also with wrist accelerations and hand force (Silverstein et al, 1987; Stock, 1991; Marras and Schoenmarklin, 1993; Schoenmarklin and Marras, 1994; Marras et al, 1995; Yassi, 1997; Mackinnon and Novak, 1997). Results were obtained from wrists during low, medium and high wrist accelerations, but in all cases under minimal loads, since no external loads were added to the mass of the hand.

Silverstein et al (1987) demonstrated, based on correlations between injury data and task properties, that high force and high repetition in the workplace are associated with an increased incidence of carpal tunnel syndrome. Marras and Schoenmarklin (1991a, 1991b) performed in depth studies on factory workers to investigate the relationship between dynamic wrist motion and upper extremity cumulative trauma disorders (UE-CTDs) by focusing on correlations between operator-reported incidence and three-dimensional wrist kinematics in the workspace. Their results suggest that the risk of developing work-related UE-CTDs increases six-fold when mean wrist accelerations in the flexion-extension plane exceed 824 deg s^{-2} compared with exposures of less than 494 deg s^{-2} (Marras and Schoenmarklin, 1993; Schoenmarklin and Marras, 1994). The influences of wrist velocity and hand acceleration on incidence were also reported to be different between high and low cumulative trauma risk groups (Marras and Schoenmarklin, 1993; Schoenmarklin et al, 1994).

Findings of the study reported in this thesis show that in the absence of any external loads, there is little or no effect of wrist activity on median nerve function for wrist accelerations less than 800 deg s^{-2}. However, for accelerations above 800 deg s^{-2} a threshold is achieved where repetitive cyclic loading of the wrist has a negative effect on median nerve function.

The development and definition of safe wrist-workload exposure limits (SWEL) as a function of mean angular acceleration reasonably concurs with

the findings of Schoenmarklin and Marras (1994). The difference in safe exposure limits over Schoenmarklin and Marras' model may be accounted for due to sample and duration of exposure differences and the reliability of health-outcome measures, where the investigators utilized self-reporting techniques.

Mean angular acceleration of the wrist may serve as an important measure for estimating the effect of occupational exposures on median nerve function. Biomechanical models incorporating angular acceleration are a powerful measure of work exposure, since the combined effect of force, frequency, posture and duration can be expressed as a unit of work. In an occupational setting, physical risk factors are not typically presented independent of each other. The expression of their combined effect as a measure of work may, therefore, facilitate the applicability of such biomechanical models to workplace task demands.

Carpal tunnel pressures can be measured using wick catheters that are inserted percutaneously. It has been shown that carpal canal pressures are elevated in normal wrists at end flexion and end extension. Patients with carpal tunnel syndrome exhibit significantly higher pressures at neutral, flexed and extended positions of the wrist and recover more slowly than normal controls after passive wrist deviations. Experimentally induced and controlled carpal canal pressures produce mild neurophysiological changes in median nerve conduction at 30 mm Hg and both sensory and motor conduction blocks at 60 mmHg and 90 mmHg.

During repeated flexion and extension of the wrist, intracellular fluid pressure increases within the carpal tunnel, producing an electroneurologic alteration in the median nerve. If prolonged, even rather low pressures could slow or obstruct venous microcirculation within the median nerve potentially leading to nerve cell necrosis.

In this study, normal wrists were repeatedly flexed and extended producing a measured threshold shift in the sensory median nerve conduction. Electrodiagnostic levels for clinical carpal tunnel syndrome might have been exceeded for the high wrist activity condition had the activity continued uninterrupted for 4 hours, well within the scope of a typical workday. At this activity level it is suspected that the repetitive flexion and

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extension of the wrist leads to increased intracellular fluid pressure within the carpal tunnel that exceeds normal physiologic capacity. Continued elevated carpal tunnel pressures adversely affect the median nerve by slowing or obstructing venous microcirculation within the nerve fibers leading to alterations in the nerve cell and its sheath. These changes were documented objectively as diminished nerve conduction and subjectively as symptoms of carpal tunnel syndrome. As sensory median nerve latency increases from normal to levels diagnostic of CTS, continued wrist activity is potentially harmful and its negative effect on the nerve may be cumulative.

The results of this study are consistent with the findings of documented epidemiological studies, in that highly repetitious exposures appear to be contributory to the development of carpal tunnel syndrome.

Opponents of the recently overturned OSHA ergonomics program standard cite the absence of objective scientific data as reasonable grounds for postponement of such a standard. Scientific data presented within the scope of this thesis demonstrates a dose-response relationship between wrist activity and median nerve function, thereby supporting the premise of a workplace ergonomics standard. Further, findings of this study present opportunity for continued research toward the establishment of safe exposure limits for hand intensive activities.

7.6 Practical Applications of the Findings

Advanced measurement systems employed in this study are still in their infancy. As further technological gains are achieved, it is anticipated that the techniques utilized herein will be used to explore and quantify etiological mechanisms in carpal tunnel syndrome across wide-ranging stressor and population variables. It is expected that these technologies will one day be exportable to the workplace as a tool for measuring the effects of various ergonomic risk factors in specific hand-intensive operations.

7.6.1 Workplace Hazard Surveillance and Intervention

The research explored in this thesis presents the foundation for establishment of safe wrist-workload exposure limits for hand-intensive operations. Further evaluation of effects is warranted for varying independent and combined task demands. Research should be expanded across a broader population sample, involving controls and CTS patients, to evaluate possible response differences in median nerve conduction. Further discussion of this opportunity for practical application of the findings is presented in the conclusions chapter.

7.6.2 Electrodiagnostic Value

Reference values for electrodiagnostic studies vary by method. Evaluation of available techniques directed that the sensory antidromic method was the most appropriate for this study, based on sensitivity of measures and participant tolerance. Available reference values for this technique are limited to Kimura (1979), Carroll (1987), and Jackson and Clifford (1989).

7.6.2.1 Sensitivity of Median Nerve Function Measures

Reference values (Kimura, 1979; Carroll, 1987; Jackson and Clifford, 1989) typically express normal values and empirical limits of normal in terms of onset and peak latencies. Software algorithms may miscalculate onset latency, where a false onset point is sometimes detected due to signal artifact. The reliability of onset latency as an objective measure of median nerve function is therefore questionable. Peak latency is identifiable within the waveform response to a presented stimulus as the time at which the greatest number of nerve fibers responds. Software algorithms are able to accurately identify this measure with repeatability. Sensory nerve conduction velocity is a distance corrected value of peak latency.

Results of this study indicate that conduction velocity (as a function of peak latency) is the most sensitive indicator of sensory median nerve function over time. It is suggested that conduction velocity be considered as the definitive reference value for use in electrodiagnostic studies of sensory median nerve function.

7.6.2.2 Correction Factors for Personal Characteristics

A finding of abnormal median slowing may be a normal population variant after considering age, or other immutable characteristics of the individual. Slowing of median nerve function occurs naturally with increasing age (Stetson et al, 1992; Letz and Gerr, 1994), though not necessarily leading to the development of CTS (Nathan et al, 1988b, 1992, 1998). The need to correct for normal physiologic changes in median nerve function is imperative to isolate pathologic changes responsible for nerve slowing.

Only reference values presented by Carroll (1987) offer any form of age correction, where patients are categorized into broad age ranges covering early adult (16-39), middle age (40-59) and elderly (60-82) groups. Neither Kimura (1979) nor Jackson and Clifford (1989) offer age-corrected reference values.

In this study, the effect of age / aging was found to be significantly associated with unadjusted measures of nerve conduction velocity (R=-0.345, p=0.005). However, after adjusting for covariate effects of near-nerve skin temperature measured at the fingertip, the relationship between age and SNCV was no longer significant. This observation suggests that natural slowing of median nerve function with age may be due to diminished peripheral vascularization.

7.6.2.3 Correction Factors for Nerve Temperature

Almost all of the heat effect on the hands is due to blood flow and environmental conditions. Since nerve temperature is primarily regulated by blood flow, any occupational or environmental factor that reduces blood

circulation to the hand may affect nerve function. Findings present considerations for etiologies of median neuropathy and its clinical diagnosis.

Present practices for correction of electrodiagnostic measures for low skin temperature vary widely by institution. To enhance confidence in clinical findings it is recommended that reference values for temperature-adjusted measures of sensory median nerve conduction velocity be developed. This technique could improve the sensitivity and specificity of electrodiagnostic tests. A more accurate diagnosis of mild neuropathies, such as carpal tunnel syndrome, might be possible with this technique, thereby reducing personal suffering as well as associated costs.

CHAPTER 8: CONCLUSIONS

Across the study population of clinically asymptomatic female participants, a change in median nerve performance was produced. This significant effect was evoked due to imposed physical stressors, where other within-subject effects on nerve conduction were constant.

The null hypothesis was thus rejected. Findings support the conclusion that wrist activity does produce an effect on median nerve function, where nerve conduction decreases as wrist activity increases. A dose response relationship between work intensity, exposure time and median nerve conduction velocity was demonstrated.

Wrist activity measures of mean angular acceleration of the wrist presented the strongest association with nerve performance. Using regression analysis, a maximum safe wrist-workload exposure limit of 0.91 repetitions per minutes is proposed. Limitations of this proposed threshold value are discussed.

A biomechanical model is presented to calculate the effect of independent and combined physical risk factors on tendon moments at the wrist. This model offers a method by which findings of the study can be employed for workplace exposure surveillance and the development of ergonomic recommendations for workstation design.

8.1 Significance of this Study

Prior research in this area has suggested an association between repetitive wrist activity and incidence of work-related carpal tunnel syndrome. A quantitative laboratory study was required to further explore the biomechanical basis of WR-CTS beyond epidemiological evidence. In this study, a systematic, time-factored transient shift in median nerve conduction was produced across normal individuals. While not necessarily indicative of the pathological process of carpal tunnel syndrome, a neurological basis for WR-CTS has been demonstrated, which furthers our understanding of the mechanism by which wrist activity contributes to median nerve impairment.

The foundation for a dynamic stress test for the assessment of carpal tunnel syndrome has also been created.

8.2 Future Work

The research documented in this thesis presents a foundation for the development of a "Dynamic Median Nerve Stress Test". The underlying premise of this test is very similar to the widely known Cardiovascular Stress Test, in that susceptibility to the development of a disabling condition can be evaluated under controlled conditions. Susceptibility includes exposure to occupational, environmental and personal risk factors.

The Dynamic Median Nerve Stress Test would involve the performance of a repetitive motion activity of the wrist during which changes in the function of the median nerve are closely monitored. This test might prove to be valuable both as an important research tool for ergonomists, as well as a provocative clinical test for physicians and other health care professionals.

Safe exposure limits are necessary for the effective management and control of physical risk factors. Dynamic testing under work-like conditions is a most effectual method by which safe exposure limits can be determined. As a research tool, the Dynamic Median Nerve Stress test could offer a standardized technique toward the establishment of safe wrist-workload exposure limits (SWELs). Further evaluation of workload effects is warranted for varying independent and combined task demands. Research should be expanded across a broader population sample, involving controls and CTS patients, to evaluate possible response differences in median nerve conduction. Through this process, the presented biomechanical model for tendon forces at the wrist could also be validated and refined.

Katz et al (1991) stated that there is limited diagnostic value of the NIOSH component tests, indicating that effective screening for carpal tunnel syndrome awaits improved diagnostic techniques. As a diagnostic tool, the Dynamic Median Nerve Stress Test might prove to be more sensitive and more specific than existing electrophysiologic techniques. This could facilitate

a more accurate diagnosis of mild neuropathies, including carpal tunnel syndrome.

With each improvement in technique or technology, the sensitivity of measures for early detection of mild carpal tunnel syndrome increases. Efforts in this area will be most rewarding, since it is through early diagnosis or better prevention that pain and suffering, associated costs and lost worktime will be substantially reduced.

REFERENCES

AAEM - American Association of Electrodiagnostic Medicine (1993). Practice parameter for electrodiagnostic studies in carpal tunnel syndrome. *Muscle and Nerve* 16: 1390-1414.

Allen C.W. (1995). Weight of evidence links obesity, fitness to carpal tunnel syndrome. *Occupational Health and Safety Magazine.* Steven's Publishing, Waco, TX.

Armstrong T.J. (1976). Circulatory and local muscle responses to static manual work. University of Michigan, Ann Arbor, MI. Ph.D. dissertation.

Armstrong T.J. and Chaffin D.B. (1979a). Carpal tunnel syndrome and selected personal attributes. *Journal of Occupational Medicine* 21(7): 481-486.

Armstrong T.J. and Chaffin D.B. (1979b). Some biomechanical aspects of the carpal tunnel. *Journal of Biomechanics* 12: 567-570.

Armstrong T.J., Castelli W.A., Evans F.G. and Diaz-Perez R. (1984). Some histological changes in the carpal tunnel contents and their biomechanical implications. *Journal of Occupational Medicine* 26(3): 197-201.

Armstrong T.J. (1986). Upper extremity posture: Definition, measurement and control. In Wilson J., Corlett E. N. and Manenica I. *The ergonomics of working postures: Models, methods and cases.* Taylor and Francis, Bristol, PA: 59-73.

Armstrong, T.J., Radwin, R.G., Hansen, D.J., Kennedy, K.W. (1986). Repetitive trauma disorders: job evaluation and design. Human Factors, 28:325-336

Armstrong T.J., Fine L.J., Goldstein S.A., Lifshitz Y.R., et al. (1987a). Ergonomic considerations in hand and wrist tendinitis. *Journal of Hand Surgery* 12(5, pt. 2): 830-837.

Armstrong T.J., Fine L.J., Radwin R.G. and Silverstein B.A. (1987b). Ergonomics and the effects of vibration in hand-intensive work. *Scandinavian Journal of Work, Environment and Health* 13(4): 286-289.

Armstrong T.J., Buckle, P., Fine, L.J., Hagberg, M., et al. (1993). A conceptual model for work-related neck and upper-limb musculoskeletal disorders. Scandinavian Journal of Work, Environment & Health, 19:73-84.

Atcheson S.G., Ward J.R. and Lowe W. (1998). Concurrent medical disease in work-related carpal tunnel syndrome. *Archives of Internal Medicine* 158(14): 1506-1512.

Atisook R., Benjapibal M., Sunsaneevithayakul P. and Roongpishthipong A. (1995). Carpal tunnel syndrome during pregnancy: Prevalence and blood level of pyridoxine. *Journal of the Medical Association of Thailand* 78(8): 410-414.

Atroshi I., Johnsson R. and Springhorn A. (1998). Self-administered outcome instrument in carpal tunnel syndrome: Reliability, validity and responsiveness evaluated in 102 patients. *Acta Orthop Scand* 69(1): 82-88.

Atroshi I., Gummesson C., Johnsson R., Ornstein E., at al (1999). Prevalence of carpal tunnel syndrome in a general population. *JAMA* 282(2): 153-158.

Aulisa L., Tamburrelli F., Padua R., Romanini E., et al. (1998). Carpal tunnel syndrome: Indication for surgical treatment based on electrophysiologic study. *Journal of Hand Surgery [Am]* 23(4): 687-691.

Bartol A. (1995). Study of nerve function related to occupational repetitive motion injury and carpal tunnel syndrome. Ph.D. Thesis; Drexel University, Philadelphia, PA.

Bay B.K., Sharkey N.A. and Szabo R.M. (1997). Displacement and strain of the median nerve at the wrist. *Journal of Hand Surgery* 22A(4): 621-627.

Bernard B.P. (1997). Musculoskeletal disorders and workplace factors: a critical review of epidemiological evidence for work-related musculoskeletal disorders of the neck, upper extremity and back. US Department of Health and Human Services. Washington, DC. Report # 97-141.

Bernstein R.A. (1994). Endoscopic carpal tunnel release. *Connecticut Medicine* 58(7): 387-394.

Bessette L., Sangha O., Kuntz K.M., Keller R.B., et al. (1998). Comparative responsiveness of generic versus disease-specific and weighted versus unweighted health status measures in carpal tunnel syndrome. *Med Care* 36(4): 491-502.

Bland J.D. (2000). The value of the history in the diagnosis of carpal tunnel syndrome. *Journal of Hand Surgery* 25(5): 445-450.

Bonel H.M., Heuck A, Frei K.A., Herrmann K., et al (2001). Carpal tunnel syndrome: assessment by turbo-spin echo, spin echo, and magnetization transfer imaging applied in a low-field MR system. *Journal of Computer-Assisted Tomography* 25(1): 137-145.

Boniface S.J., Morris I. and Macleod A. (1994). How does neurophysiological assessment influence the management and outcome of patients with carpal tunnel syndrome? *British Journal of Rheumatology* 33: 1169-1170.

Borg G.A. (1982). Psychophysical bases of perceived exertion. *Medical Science of Sports Exercise* 14(5): 377-381.

Brahme S.K., Hodler J., Braun R.M., Sebrechts C., et al. (1997). Dynamic MR imaging of carpal tunnel syndrome. *Skeletal Radiology* 26(8): 482-487.

Brogmus G.E. and Marko R. (1990). Cumulative trauma disorders of the upper extremities - the magnitude of the problem in US industry. IEA Conference on Human Factors in Design for Manufacturability and Process Planning, Honolulu, Hawaii.

Brogmus G.E., Webster B. and Sorock G. (1994). Recent trends in cumulative trauma disorders of the upper extremities in the United States. Twelfth triennial congress of the International Ergonomics Association, Toronto, Canada, International Ergonomics Association.

Brogmus G.E. (1995). Reporting of cumulative trauma disorders of the upper extremities may be leveling off in the US. Human Factors and Ergonomics Society 39th Annual Meeting, San Diego, CA.

Brogmus G.E., Sorock G. and Webster B. (1996). Recent trends in work-related cumulative trauma disorders of the upper extremities in the United States - an evaluation of possible reasons. *Journal of Occupational and Environmental Medicine* 38(4): 401-411.

Buchthal F., Rosenfalck A. and Trojaborg W. (1974). Electrophysiological findings in entrapment of median nerve at wrist and elbow. *Journal of Neurology, Neurosurgery and Psychiatry* 37: 340-360.

Cannon L.J., Bernacki E.J. and Walter S.D. (1981). Personal and occupational factors associated with carpal tunnel syndrome. *Journal of Occupational Medicine* 23(4): 255-258.

Capone L. Pentore R., Lunazzi C. and Schonhuber R. (1998). Pitfalls in using the ring finger test alone for the diagnosis of carpal tunnel syndrome. *Italian Journal of Neurological Science* 19(6): 387-390.

Carneiro R.S. (1999). Carpal tunnel syndrome: the cause dictates the treatment. *Cleveland Clinical Journal of Medicine* 66(3): 159-164.

Carroll G. (1987). Comparison of median and radial nerve sensory latencies in the electrophysiological diagnosis of carpal tunnel syndrome. *Electroencepholography and Clinical Neurophysiology* 68: 101-106.

Chabon S.J. (1985). Carpal tunnel syndrome - a medical and occupational disease. *PA Outlook* 4:11-14, 16.

Chalk C.H. and Dyck P.J. (1993). Ischemic neuropathy. In Dyck P. J. and Thomas P. K. (Eds.) *Peripheral neuropathy*. W.B. Saunders Company, Philadelphia, PA.

Chammas M., Bousquet P., Renard E., Poirier J.L., et al. (1995). Dupuytren's disease, carpal tunnel syndrome, trigger digit and diabetes mellitus. *Journal of Hand Surgery* 20(1): 109-114.

Chang M.H., Chang H.T., Lee S.S., Ger L.P., et al. (1998). Oral drug of choice in carpal tunnel syndrome. *Neurology* 51(2): 390-393.

Chao E.Y. (1976). Three-dimensional force analysis of finger joints in selected isometric hand functions. *Journal of Biomechanics* 9(6): 387-396.

Chidgey L.K., Szabo R.M. and Kolack B. (1989). Effects of elevation on nerve function in an acute upper extremity nerve compression model. *Journal of Orthopedic Research* 7(6): 783-791.

Choi S.J. and Ahn D.S. (1998). Correlation of clinical history and electrodiagnostic abnormalities with outcome after surgery for carpal

tunnel syndrome. *Plastic and Reconstructive Surgery* 102(7): 2374-2380.

Clauser C., Tebbetts I., Bradtmiller B., McConville J., et al. (1988). Measurer's handbook: U.S. army anthropometric survey. United States Army, Natick Research Development and Engineering Center, Natick, MA.

Cobb T.K., Dalley B.K., Posteraro R.H. and Lewis R.C. (1992). The carpal tunnel as a compartment: An anatomic perspective. *Othropaedic Reviews* 21(4): 451-453.

Cobb T.K., An K.N. and Cooney W.P. (1995). Externally applied forces to the palm increase carpal tunnel pressure. *Journal of Hand Surgery [Am]* 20(2): 181-185.

Cobb T.K., Bond J.R., Cooney W.P. and Metcalf B.J. (1997). Assessment of the ratio of carpal contents to carpal tunnel volume in patients with carpal tunnel syndrome: a preliminary report. *Journal of Hand Surgery [Am]* 22(4): 635-639.

D'Arcy C.A. and McGee S. (2000). Does this patient have carpal tunnel syndrome? *JAMA* 283(23):3110-3117.

Dahlin L.B., Danielsen N., Ehira T., Lundborg G., et al. (1986). Mechanical effects of compression of peripheral nerves. *Journal of Biomechanical Engineering* 108(2): 120-122.

Dempster W.T. (1955). Space requirements of the seated operator. Aerospace Medical Research Laboratories, Ohio.

DeStefano F., Nordstrom D.L. and Vierkant R.A. (1997). Long-term symptom outcome of carpal tunnel syndrome and its treatment. *Journal of Hand Surgery [Am]* 22(2): 200-210.

Ellis J., Folkers K., Watanabe T., Kaji M., et al. (1979). Clinical results of a cross-over treatment with pyridoxine and placebo of the carpal tunnel syndrome. *American Journal of Clinical Nutrition* 32(10): 2040-2046.

Ferry S., Silman A.J., Pritchard T., Keenan J., et al. (1998a). The association between different patterns of hand symptoms and objective evidence of median nerve compression: a community-based survey. *Arthritis Rheum* 41(4): 720-724.

Ferry S., Pritchard T., Keenan J., Croft P., et al. (1998b). Estimating the prevalence of delayed median nerve conduction in the general population. *British Journal of Rheumatology* 37(6): 630-635.

Ferry S., Hannaford P., Warskyj M., Lewis M. and Croft P. (2000). Carpal tunnel syndrome: a nested case-control study of risk factors in women. *American Journal of Epidemiology* 151(6): 566-574.

Fine L.J., Silverstein B.A., Armstrong T.J., Anderson C.A., et al. (1986). Detection of cumulative trauma disorders of upper extremities in the workplace. *Journal of Occupational Medicine* 28(8): 674-678.

Forman D.L., Watson H.K., Caulfield K.A., Shenko J., et al. (1998). Persistent or recurrent carpal tunnel syndrome following prior endoscopic carpal tunnel release. *Journal of Hand Surgery [Am]* 23(6): 1010-1014.

Franklin G.M., Haug J., Heyer N., Checkoway H., et al. (1991). Occupational carpal tunnel syndrome in Washington State 1984-1988. *American Journal of Public Health* 81(6): 741-746.

Fuchs, P.C., Nathan, P.A. and Myers, L.D. (1991). Synovial histology in carpal tunnel syndrome. *Journal of Hand Surgery*, 16A(4): 753-758.

Galassi E., Benfenati A., Tognetti F. and Pozzati E. (1980). Persistence of the median artery: possible cause of the carpal tunnel syndrome. *Riv Neurology* 50(3): 159-166.

Gelberman R.H., Hergenroeder P.T., Hargens A.R., Lundborg G.N., et al. (1981). The carpal tunnel syndrome - a study of carpal canal pressures. *The Journal of Bone and Joint Surgery* 63A(3): 380-383.

Gellman H., Gelberman R.H., Tan A.M. and Botte M.J. (1986). Carpal tunnel syndrome: An evaluation of the provocative diagnostic tests. *Journal of Bone and Joint Surgery* 68A: 735-737.

Ghavanini M.R. and Haghighat M. (1998). Carpal tunnel syndrome: reappraisal of five clinical tests. *Electromyography and Clinical Neurophysiology* 38(7): 437-441.

Giannini F., Passero S., Cioni R., Paradiso C., et al. (1991). Electrophysiologic evaluation of local steroid injection in carpal tunnel syndrome. *Archives of Physical Medicine and Rehabilitation* 72: 738-742.

Giersiepen K., Eberle A. and Pohlabeln H. (2000). Gender differences in carpal tunnel syndrome: occupational and non-occupational risk factors in a population-based case-control study. *Annals of Epidemiology* 10(7): 481.

Goldstein S.A., Armstrong T.J., Chaffin D.B. and Mathews L.S. (1987). Analysis of cumulative strain in tendons and tendon sheaths. *Journal of Biomechanics* 20(1): 1-6.

Goodman R.C. (1992). An aggressive return-to-work program in surgical treatment of carpal tunnel syndrome a comparison of costs. *Plastic and Reconstructive Surgery* 89(4): 715-717.

Gossett J.G. and Chance P.F. (1998). Is there a familial carpal tunnel syndrome? An evaluation and literature review. *Muscle and Nerve* 21(11): 1533-1536.

Green R.A. and Briggs C.A. (1989). Effect of overuse injury and the importance of training on the use of adjustable workstations by keyboard operators. *Journal of Occupational Medicine* 31(6): 557-562.

Gross C.M. (1988). Diagnostic criteria for cumulative trauma disorders of the upper extremity. Biomechanics Corporation of America, Melville, New York.

Gross C.M. (1996). The Right Fit. Productivity Press, Portland, OR.

Gross C., Lloyd J.D., Nelson A. and Haslam R.A. (1998). Carpal tunnel syndrome: A review of the literature with recommendations for further research. *Florida Journal of Public Health* 9(1) 22-28.

Grundfest H. (1936). Effects of hydrostatic pressure upon the excitability, the recovery and the potential sequence of frog nerve. *Quantitative Biology* 1936(4): 1979.

Gupta S.K. and Benstead T.J. (1997). Symptoms experienced by patients with carpal tunnel syndrome. *Canadian Journal of Neurological Science* 24(4): 338-342.

Hagberg M., Silverstein, B., Wells, R., Smith, M., et al. (1995). Work Related Musculoskeletal Disorders (WMSDs): A Reference Book for Prevention. London: Taylor and Francis Ltd.

Halar E.M., DeLisa J.A. and Soine T.L. (1983). Nerve conduction studies in upper extremities: skin temperature corrections. *Archives of Physical Medicine and Rehabilitation* 64(9): 412-416.

Hamanaka I., Okutsu I., Shimizu K., Takatori Y., et al. (1995). Evaluation of carpal canal pressure in carpal tunnel syndrome. *Journal of Hand Surgery [Am]* 20(5): 848-854.

Herrick R.T. and Herrick S.K. (1987). Thermography in the detection of carpal tunnel syndrome and other compressive neuropathies. *Journal of Hand Surgery [Am]* 12(5, pt 2): 943-949.

Higgs P.E., Edwards D.F., Martin D.S. and Weeks P.M. (1997). Relation of preoperative nerve-conduction values to outcome in workers with surgically treated carpal tunnel syndrome. *Journal of Hand Surgery [Am]* 22(2): 216-221.

Hildenhage O., Rehu U. and Holdorff B. (1985). Electroneurography in the carpal tunnel syndrome - selective antidromic sensory and orthodromic measurement of the median nerve in the wrist-palm segment with surface electrodes. *EEG EMG Z Elekroenzephalogr Verwandte Geb EED* 16(2): 108-113.

Hitchcock T. and D'Silva J. (1995). Understanding Carpal Tunnel Syndrome. Anatomical Chart Company, Skokie, Illinois.

Horch R.E., Allmann K.H., Laubenberger J., Langer M., et al. (1997). Median nerve compression can be detected by magnetic resonance imaging of the carpal tunnel. *Neurosurgery* 41(1): 76-82.

Huynh H. and Feldt L.S. (1976). Estimation of the Box correction for degrees of freedom from sample data in the randomized block and split-plot designs. *Journal of Educational Statistics* 1: 69-82.

Jackson D.A. and Clifford J.C. (1989). Electrodiagnosis of mild carpal tunnel syndrome. *Archives of Physical Medicine and Rehabilitation* 70: 199-204.

Kapit W. and Elson L.M. (1977). The anatomy coloring book. Harper and Row Publishers, New York.

Katz J.N., Larson M.G., Fossel A.H. and Liang M.H. (1991). Validation of a surveillance case definition of carpal tunnel syndrome. American Journal of Public Health; 81(2):189-193.

Katz R.T. (1994). Carpal tunnel syndrome: a practical review. *American Family Physician* 49(6): 1371-1379.

Kaul M.P., Pagel K.J. and Dryden J.D. (2000). Lack of predictive power of the "tethered" median stress test in suspected carpal tunnel syndrome. *Arch Phys Med Rehabil* 80(3): 348-350.

Keir P.J. and Wells R.P. (1992). MRI of the carpal tunnel: Implications for carpal tunnel syndrome. S. Kumar. *Advances in Industrial Ergonomics and Safety IV.* Taylor and Frances, London.

Keir P.J., Wells R.P., Ranney D.A. and Lavery W. (1997). The effects of tendon load and posture on carpal tunnel pressure. *Journal of Hand Surgery [Am]* 22(4): 628-634.

Keir P.J., Bach J.M. and Rempel D.M. (1998a). Effects of finger posture on carpal tunnel pressure during wrist motion. *Journal of Hand Surgery [Am]* 23(6): 1004-1009.

Keir P.J., Bach J.M. and Rempel D.M. (1998b). Fingertip loading and carpal tunnel pressure: differences between a pinching and a pressing task. *Journal of Orthopedic Research* 16(1): 112-115.

Keppel G. (1991). Design and analysis: A researcher's handbook. Prentice Hall, Englewood Cliffs, NJ: 136-184.

Kern B.C., Brock M., Rudolph K.H. and Logemann H. (1993). The recurrent carpal tunnel syndrome. *Zentralblatt fur Neurochirurgie* 54(2): 80-83.

Kerwin G., Williams C.S. and Seiler J.G. (1996). The pathophysiology of carpal tunnel syndrome. *Hand Clinics* 12(2): 243-251.

Kiesler S. and Finholt T. (1988). The mystery of RSI. *American Psychologist* 43: 1004-1015.

Kimura J. (1979). The carpal tunnel syndrome - Localization of conduction abnormalities within the distal segment of the median nerve. *Brain* 102: 619-635.

Korthals J.K. and Wisniewski H.M. (1975). Peripheral nerve ischemia. Part 1-Experimental model. *Journal of Neurological Science* 24: 65-76.

Korthals J.K., Korthals M.A. and Wisniewski H.M. (1978). Peripheral nerve ischemia. Part 2-Accumulation of organelles. *Annals of Neurology* 4(6): 487-498.

Kuhlman K.A. and Hennessey W.J. (1997). Sensitivity and specificity of carpal tunnel syndrome signs. *American Journal of Physical Medicine Rehabilitation* 76(6): 451-457.

Kuorinka I. and Forcier L. (1995). Work related musculoskeletal disorders (WMSDs): a reference book for prevention. Taylor and Francis, Bristol, PA.

LaBan M.M., Friedman N.A. and Zemenick G.A. (1986) "Tethered" median nerve stress test in chronic carpal tunnel syndrome. *Arch Phys Med Rehabil* 67(11):803-4.

Lam N. and Thurston A. (1998). Association of obesity, gender, age and occupation with carpal tunnel syndrome. *Australian and New Zealand Journal of Surgery* 68(3): 190-193.

Lantigua-Peterson T. (1999). The worker's disease: an ailment affecting cubicle dwellers has a long history in an age of industry. Tampa Tribune, Tampa, FL. June 6.

Laroy, V. Spaans F. and Reulen J. (1999). Nerve conduction studies show no exclusive ulnar or median innervation of the ring finger. *Clinical Neurophysiology* 110(8): 1492-1497.

Lavey E.B. and Pearl R.M. (1981). Patent median artery as a cause of carpal tunnel syndrome. *Annals of Plastic Surgery* 7(3): 236-238.

Leclerc A., Franchi P., Cristofari M.F., Delemotte B., et al. (1998). Carpal tunnel syndrome and work organization in repetitive work: a cross sectional study in France. *Occupational and Environmental Medicine* 55(3): 180-187.

Lee D.H., Masear V.R., Meyer R.D., et al. (1992). Endoscopic carpal tunnel release: a cadaver study. *Journal of Hand Surgery (American)* 17:1003-1008.

Lehtinen I., Kirjavainen T., Hurme M., Lauerman H., et al. (1996). Sleep-related disorders in carpal tunnel syndrome. *Acta Neurol Scand* 93(5): 360-365.

Letz R. and Gerr F. (1994). Covariates of human peripheral nerve function: Nerve conduction velocity and amplitude. *Neurotoxicology and Teratology* 16(1): 95-104.

Loslever P. and Ranaivosoa A. (1993). Biomechanical and epidemiological investigation of carpal tunnel syndrome at workplaces with high risk factors. *Ergonomics* 36(5): 537-554.

Luchetti R., Schoenhuner R., DeCicco G., Alfarano M., et al. (1989). Carpal tunnel pressure. *Acta Orthop Scand* 60(4): 397-399.

Luchetti R., Schoenhuber R., Alfarano M., Deluca S., et al. (1990). Carpal tunnel syndrome - correlations between pressure measurement and intraoperative electrophysiological nerve study. *Muscle and Nerve* 13: 1164-1168.

Luchetti R., Schoenhuber R. and Nathan P. (1998). Correlation of segmental carpal tunnel pressures with changes in hand and wrist positions in patients with carpal tunnel syndrome and controls. *Journal of Hand Surgery [Br]* 23(5): 598-602.

Lundborg G. (1970). Ischemic nerve injury: Experimental studies on intraneural microvascular pathophysiology and nerve function in a limb subjected to temporary circulatory arrest. *Scandinavian Journal of Plastic and Reconstructive Surgery* 6(1): 113.

Lundborg G., Gelberman R.H., Minteer-Convery M., Lee Y.F., et al. (1982). Median nerve compression in the carpal tunnel - functional response to experimentally induced controlled pressure. *Journal of Hand Surgery [Am]* 7(3): 252-259.

Lundborg G. and Dahlin L.B. (1989). Pathophysiology of nerve compression. In Szabo R. M. (Ed.) *Nerve Compression Syndromes.* SLACK Incorporated Publishers, Thorofare, New Jersey. 15-39.

Luyendijk W. (1986). The carpal tunnel syndrome: The role of a persistent median artery. *Acta Neurochir* 79(1): 52-57.

Macdonnel R.A., Schwartz M.S. and Swash M. (1990). Carpal tunnel syndrome - which finger should be tested? An analysis of sensory conduction in digital branches of the median nerve. *Muscle and Nerve* 13(7): 601-606.

Mackinnon S.E. and Novak C.B. (1997). Repetitive strain in the workplace. *Journal of Hand Surgery [Am]* 22(1): 2-18.

MacLeod D. (1996). Ergonomics success in the meat industry. Clayton Environmental Consultants, Edison, NJ.

Madsen F.H. and Jensen O.C. (1991). The carpal tunnel syndrome. An occupational disease? *Ugeskr Laeger* 153(24): 1725-1727.

Marras W.S. and Schoenmarklin R.W. (1991a). Quantification of wrist motion in highly repetitive hand-intensive industrial jobs. National Institute for Occupational Safety and Health, Washington, DC. Report # PB91-226191.

Marras W.S. and Schoenmarklin R.W. (1991b). Wrist motions and CTD risk in industrial and service environments. Designing for everyone: Proceedings of the Eleventh Congress of the International Ergonomics Association, Taylor and Francis. 36-38.

Marras W.S. and Schoenmarklin R.W. (1993). Wrist motions in industry. *Ergonomics* 36(4): 341-351.

Marras W.S., Marklin R.W., Greenspan G.J. and Lehman K.R. (1995). Quantification of wrist motions during scanning. *Human Factors* 37(2): 412-423.

Martinez-Albaladejo M., Noribela-Gomez M., Perez-Florez D. and Acosta P.Z. (1993). Carpal tunnel syndrome. *Anales de Medicina Interna* 10(11): 542-546.

Massy-Westropp N, Grimmer K. and Bain G. (2000). A systematic review of the clinical diagnostic tests for carpal tunnel syndrome. *Journal of Hand Surgery* 25(1): 120-127.

Matias A.C., Salvendy G. and Kuczek T. (1998). Predictive models of carpal tunnel syndrome causation among VDT operators. *Ergonomics* 41(2): 213-226.

McDiarmid M., Oliver M., Ruser J. and Gucer P. Male and female rate differences in carpal tunnel syndrome: personal attributes or job tasks? *Environmental Research* 83(1): 23-32.

McManis P.G., Low P.A. and Lagerlund T.D. (1993). Microenvironment of nerve: blood flow and ischemia. In Dyck P. J. and Thomas P. K. (Eds.).

Peripheral neuropathy. W.B. Saunders Company, Philadelphia, PA: 453-473.

Melvin J.L., Schuchmann J.A. and Lanese R.R. (1973). Diagnostic specificity of motor and sensory nerve conduction variables in the carpal tunnel syndrome. *Archives of Physical Medicine and Rehabilitation* 54(2): 69-74.

Meyers S., Cros D., Sherry B. and Vermeire P. (1989). Liquid crystal thermography: Quantitative studies of abnormalities in carpal tunnel syndrome. *Neurology* 39(11): 1465-1469.

Miller B.K. (1993). Carpal tunnel syndrome - a frequently misdiagnosed common hand problem. *Nurse Practitioner* 18(12): 52-56.

Moersch P. (1938). Median thenar neuritis. Proceedings of Surgical Meeting of the Mayo Clinic. 220:222.

Monagle K., Dai G., Chu A., Burnham R.S. and Snyder R.E. (1999). Quantitative MR imaging of carpal tunnel syndrome. *American Journal of Roentgenology* 172(6): 1581-1586.

Morgenstern H., Kelsh M., Kraus J. and Margolis W. (1991). A cross-sectional study of hand/wrist symptoms in female grocery checkers. *American Journal of Industrial Medicine* 20(2): 209-218.

Murata K., Araki S. and Aono K. (1990). Central and peripheral nervous system effects of hand-arm vibrating tool operation: A study of brainstem auditory-evoked potential and peripheral nerve conduction velocity. *International Archives of Occupational and Environmental Health* 62(3): 183-187.

Nathan P.A., Meadows K.D. and Doyle L.S. (1988a). Sensory segmental latency values of the median nerve for a population of normal

individuals. *Archives of Physical Medicine and Rehabilitation* 69(7): 499-501.

Nathan P.A., Meadows K.D. and Doyle L.S. (1988b). Relationship of age and sex to sensory conduction of the median nerve at the carpal tunnel and association of slowed conduction with symptoms. *Muscle and Nerve* 11(11): 1149-1153.

Nathan P.A., Keniston R.C., Myers L.D. and Meadows K.D. (1992). Longitudinal study of median nerve sensory conduction in industry - relationship to age, gender, hand dominance, occupational hand use and clinical diagnosis. *Journal of Hand Surgery* 17A(5): 850-857.

Nathan P.A., Takigawa K., Keniston R.C., Meadows K.D., et al. (1994). Slowing of sensory conduction of the median nerve and carpal tunnel syndrome in Japanese and American industrial workers. *Journal of Hand Surgery* 19B(1): 30-34.

Nathan, P.A., Keniston, R.C., Lockwood, R.S. and Meadows, K.D. (1996). Tobacco, caffeine, alcohol, and carpal tunnel syndrome in American industry. *Journal of Occupational and Environmental Medicine*, 38(3): 290-298.

Nathan P.A., Keniston R.C., Myers L.D., Meadows K.D., et al. (1998). Natural history of median nerve conduction in industry: Relationship to symptoms and carpal tunnel syndrome in 558 hands over 11 years. *Muscle and Nerve* 21(6): 711-721.

National Academy of Sciences. (2001). Musculoskeletal disorders and the workplace: low back and upper extremities. National Academic Press, Washington, DC (pre-publication).

Neal, N.C., McManners, J. and Stirling, G.A. (1987). Pathology of the flexor tendon sheath in the spontaneous carpal tunnel syndrome. *Journal of Hand Surgery*, 12B: 229-232.

Netter F.H. (1997). Atlas of Human Anatomy. Novartis Publishers, East Hanover, NJ.

Nordstrom D.L., Vierkant R.A., DeStefano F. and Layde P.M. (1997). Risk factors for carpal tunnel syndrome in a general population. *Occupational and Environmental Medicine* 54(10): 734-740.

Nygaard O.P., Trumpy J.H. and Mellgren S.I. (1996). Recovery of sensory function after surgical decompression in carpal tunnel syndrome. *Acta Neurol Scand* 94(4): 253-257.

O'Gradaigh D. and Merry P. (2000). A diagnostic algorithm for carpal tunnel syndrome based on Baye's theorem. *Journal of Hand Surgery (British)* 25(5): 445-450.

O'Riordan J., Hayes J., Fitzgerald M.X. and Redmond J. (1995). Peripheral nerve dysfunction in adult patients with cystic fibrosis. *Irish Journal of Medical Science* 164(3): 207-208.

Olave E., Prates J.C., Gabrielli C. and Pardi P. (1997). Median artery and superficial palmar branch of the radial artery in the carpal tunnel. *Scandinavian Journal of Plastic and Reconstructive Hand Surgery* 31(1): 13-16.

Osorio A.M., Ames R.G., Jones J., Castorina J., et al. (1994). Carpal tunnel syndrome among grocery store workers. *American Journal of Industrial Medicine* 25(2): 229-245.

Padua L., LoMonaco M., Aulisa L., Tamburrelli F., et al. (1996). Surgical prognosis in carpal tunnel syndrome: usefulness of a preoperative neurophysiological assessment. *Acta Neurol Scand* 94(5): 343-346.

Padua L., LoMonaco M., Gregori B., Valente E.M., et al. (1997a). Neurophysiological classification and sensitivity in 500 carpal tunnel syndrome hands. *Acta Neurol Scand* 96(4): 211-217.

Padua L., LoMonaco M., Padua R., Tamburrelli F., et al. (1997b). Carpal tunnel syndrome: neurophysiological results of surgery based on preoperative electrodiagnostic findings. *Journal of Hand Surgery [Br]* 22(5): 599-601.

Pascual E., Giner V., Arostegui A., Conill J., et al. (1991). Higher incidence of carpal tunnel syndrome in oophorectomized women. *British Journal of Rheumatology* 30(1): 60-62.

Pease S., Lee H.H. and Johnson E.W. (1990). Forearm median nerve conduction velocity in carpal tunnel syndrome. *Electromyography and Clinical Neurophysiology* 30(5): 299-302.

Pfalzer L.A. and McPhee B. (1995). Carpal tunnel research. In Isernhagen S. (Ed.) *The comprehensive guide to work injury management.* Aspen Publishers Inc., CO.

Phalen G.S. and Kendrick J.I. (1957) Compression neuropathy of the median nerve in the carpal tunnel. *JAMA* 164: 524-530

Phalen G.S. (1966). Carpal tunnel syndrome - Seventeen years experience in diagnosis and treatment of 654 hands. *Journal of Bone and Joint Surgery* 48A(2): 211-228.

Pheasant S. (1994). Ergonomics work and health. Macmillan publishing, London.

Putz-Anderson V. (1988). Cumulative trauma disorders. A manual for musculoskeletal diseases of the upper limbs. Taylor and Francis.

Radack D.M., Schweitzer M.E. and Taras J. (1997). Carpal tunnel syndrome: are the MR findings a result of population bias? *Am J Roentgenol* 169(6): 1649-1653.

Radecki P. (1994). The familial occurrence of carpal tunnel syndrome. *Muscle and Nerve* 17(3): 325-330.

Radecki P. (1995). Variability in the median and ulnar nerve latencies: Implications for diagnosing entrapment. *Journal of Environmental and Occupational Medicine* 37: 1293-1299.

Ramazinni B. (1717). The diseases of workers. In Wright W. (Ed.). (1940 reprint). University of Chicago Press, Chicago, IL.

Raudino F. (2000). Tethered median nerve stress test in the diagnosis of carpal tunnel syndrome. *Electromyography and Clinical Neurophysiology* 40(1): 57-60.

Rayan G.M. (1999). Carpal tunnel syndrome between two centuries. *Journal of the Oklahoma State Medical Association* 92(10): 493-503.

Rempel D., Manojlovic R., Levinsohn D.G., Bloom T., et al. (1994). The effect of wearing a flexible wrist splint on carpal tunnel pressure during repetitive hand activity. *Journal of Hand Surgery [Am]* 19(1): 106-110.

Rempel D., Bach J.M., Gordon L. and So Y. (1998). Effects of forearm pronation/supination on carpal tunnel pressure. *Journal of Hand Surgery [Am]* 23(1): 38-42.

Robbins H. (1963). Anatomical study of the median nerve in the carpal tunnel and the etiologies of the carpal tunnel syndrome. *Journal of Bone and Joint Surgery* 45A(5): 953-966.

Robinson L.R., Rubner D.E., Wahl P.W., Fujimoto W.Y., et al. (1993). Influences of height and gender on normal nerve conduction studies. *Archives of Physical Medicine and Rehabilitation* 74(11): 1134-1138.

Roquelaure Y., Mechali S., Dano C., Fanello S., et al. (1997). Occupational and personal risk factors for carpal tunnel syndrome in industrial workers. *Scandinavian Journal of Work, Environment and Health* 23(5): 364-369.

Rosen B., Lundborg G., Abrahamsson S.O., Hagberg L., et al. (1997). Sensory function after median nerve decompression in carpal tunnel syndrome: Preoperative versus postoperative findings. *Journal of Hand Surgery [Br]* 22(5): 602-606.

Rosenbaum R.B. and Ochoa J.L. (1993). Carpal tunnel syndrome and other disorders of the median nerve. Butterworth-Heinemann Press, Boston, MA.

Rosenberger K. and Bittenbring G. (1976). Antidromic sensory action potentials of the median and ulnar nerves - normal value and discussion of methodology. *EEG EMG Z Elekroenzephalogr Verwandte Geb EED* 7(3): 133-135.

Rossier R.N. and Blair W.F. (1984). Preliminary clinical evaluation of the digital electroneurometer. *Biomedical Sciences Instrumentation* 20: 55-62.

Rozmaryn L.M., Dovelle S., Rothman E.R., Gorman K., et al. (1998). Nerve and tendon gliding exercises and the conservative treatment of carpal tunnel syndrome. *Journal of Hand Therapy* 11(3): 171-179.

Rydevik B., Lundborg G. and Bagge U. (1981). Effects of gradual compression on intraneural blood flow: An invitro study of rabbit tibial nerve. *Journal of Hand Surgery* 6: 3-12.

Sarrafian S.K., Melamed J.L. and Goshgarian G.M. (1977). Study of wrist motion in flexion and extension. *Clinical Orthopedics* 126: 153-159.

Schoenmarklin R.W. and Marras W.S. (1990). A dynamic biomechanical model of the wrist joint. Proceedings of the 34th meeting of the Human Factors Society, Orlando, FL. 805-809.

Schoenmarklin R.W. and Marras W.S. (1994). Industrial wrist motions and incidence of hand/wrist cumulative trauma disorders. *Ergonomics* 37(9): 1449-1459.

Schottland, J.R., Kirschberg, G.J., Fillingim, R., Davis, V.P., Hogg, F. (1991). Median nerve latencies in poultry processing workers: an approach to resolving the role of industrial "cumulative trauma" in the development of carpal tunnel syndrome. *Journal of Occupational Medicine*, 33(5): 627-631.

Seradge H., Jia Y.C. and Owens W. (1995). In vivo measurement of carpal tunnel pressures in the functioning hand. *Journal of Hand Surgery [Am]* 20(5): 855-859.

Seror P. (1996). The axonal carpal tunnel syndrome. *Electroencephalography and Clinical Neurophysiology* 101(3): 197-200.

Seror P. (1998). Pregnancy-related carpal tunnel syndrome. *Journal of Hand Surgery [Br]* 23(1): 98-101.

Sheng W. and Gross C.M. (1988). Carpal tunnel syndrome a review of the literature. Biomechanics Corporation of America, Melville, New York.

Silverstein, B.A. (1985). The prevalence of upper extremity cumulative trauma disorders in industry. The University of Michigan, Ann Arbor, MI. Ph.D. dissertation.

Silverstein B.A., Fine L.J. and Armstrong T.J. (1986). Hand wrist cumulative trauma disorders in industry. *British Journal of Industrial Medicine* 43(11): 779-784.

Silverstein B.A., Fine L.J. and Armstrong T.J. (1987). Occupational factors and carpal tunnel syndrome. *American Journal of Industrial Medicine* 11(3): 343-358.

Silverstein B.A., Welp E., Nelson N. and Kalat J. (1998). Claims incidence of work-related disorders of the upper extremities: Washington state, 1987 through 1995. *American Journal of Public Health* 88(12): 1827-1833.

Simpson J.A. and Carpendale (1956). Electrical signs in the diagnosis of carpal tunnel and related syndromes. *Journal of Neurology Neurosurgery and Psychiatry* 19: 275-280.

Slater R.R. (1999). Carpal tunnel syndrome: current concepts. Journal of the Southern Orthopedic Association 8(3).

Smith E.M., Sonstegard D.A. and Anderson W.H. (1977). Carpal tunnel syndrome - contribution of flexor tendons. *Archives of Physical Medicine and Rehabilitation* 58: 379-385.

Smith T. (1998). Near-nerve versus surface electrode recordings of sensory nerve conduction in patients with carpal tunnel syndrome. *Acta Neurol Scand* 98(4): 280-282.

Snook S.H. (1990). Cumulative trauma disorders. Liberty Mutual Research Center, Hopkinton MA.

Solomon D.H., Katz J.N., Bohn R., Mogun H. and Avorn J. (1999). Nonoccupational risk factors for carpal tunnel syndrome. *Journal of General Internal Medicine* 14(5): 310-314.

Stallings S.P., Kasdan M.L., Soergel T.M. and Corwin H.M. (1997). A case-control study of obesity as a risk factor for carpal tunnel syndrome in a population of 600 patients presenting for independent medical examination. *Journal of Hand Surgery* 22(2): 211-215.

Stetson D.S., Albers J.W., Silverstein B.A. and Wolfe R.A. (1992). Effects of age sex and anthropometric factors on nerve conduction measures. *Muscle and Nerve* 15(10): 1095-1104.

Stock S.R. (1991). Workplace ergonomic factors and the development of musculoskeletal disorders of the neck and upper limbs - A meta-analysis. *American Journal of Industrial Medicine* 19: 87-107.

Stohr M. (1980). Modification of the recovery cycle of human median nerve by ischemia. *Journal of Neurological Science* 51: 171-180.

Stoll C. and Maitrot D. (1998). Autosomal dominant carpal tunnel syndrome. *Clin Genet* 54(4): 345-348.

Stolp-Smith K.A., Pascoe M.K. and Ogburn P.L. (1998). Carpal tunnel syndrome in pregnancy: frequency, severity, and prognosis. *Archives of Physical Medicine and Rehabilitation* 79(10): 1285-1287.

Sucher B.M. (1993). Myofascial release of carpal tunnel syndrome. *Journal of American Osteopathic Association* 93(1): 92-94 , 100-101.

Sugimoto H., Miyaji N. and Ohsawa T. (1994). Carpal tunnel syndrome: evaluation of median nerve circulation with dynamic contrast-enhanced MR imaging. *Radiology* 190(2): 459-466.

Sunderland S. (1976). The nerve lesion in the carpal tunnel syndrome. *Journal of Neurology, Neurosurgery and Psychiatry* 39(7): 615-626.

Sungpet A., Suphachatwong C. and Kawinwonggowit V. (1999). The relationship between body mass index and the number of sides of

carpal tunnel syndrome. *Journal of the Medical Association of Thailand* 82(2): 182-185.

Szabo, R.M. and Gelberman, R.H. (1987). The pathophysiology of nerve entrapment syndromes. *Journal of Hand Surgery*, 12A: 880-884.

Szabo R.M. (1998). Acute carpal tunnel syndrome. *Hand Clinics* 14(3): 419-429.

Szabo R.M., Slater R.R., Farver T.B., Stanton D.B. and Sharman W.K. (1999). The value of diagnostic testing in carpal tunnel syndrome. *Journal of Hand Surgery* 24(4): 704-714.

Tanaka S., Wild D.K., Seligman P.J., Halperin W. E., et al. (1995). Prevalence and work-relatedness of self-reported carpal tunnel syndrome among US workers. Analysis of the occupational health supplement data of 1988 national health interview survey. *American Journal of Industrial Medicine* 27(4): 451-470.

Tanaka S., Wild D.K., Cameron L.L. and Freund E. (1997). Association of occupational and non-occupational risk factors with the prevalence of self-reported carpal tunnel syndrome in a national survey of the working population. *American Journal of Industrial Medicine* 32(5): 550-556.

Tanzer, R.C. (1959). The carpal tunnel syndrome - a clinical and anatomical study. *Journal of Bone and Joint Surgery*, 41A(4): 626-634.

Tetro A.M., Evanoff B.A., Hollstein S.B. and Gelberman R.H. (1998). A new provocative test for carpal tunnel syndrome: assessment of wrist flexion and nerve compression. *Journal of Bone and Joint Surgery [Br]* 80(3): 493-498.

Thurston A.J. and Krause B.L. (1988). The possible role of vascular congestion in carpal tunnel syndrome. *Journal of Hand Surgery* 13B(4): 397-399.

Trojaborg W.T., Moon A., Andersen B.B. and Trojaborg N.S. (1992). Nerve conduction parameters in normal subjects related to age, gender, temperature, and height: a reappraisal. *Muscle and Nerve* 15(6): 666-671.

US Department of Labor. (1982-2000). Worker injuries and illnesses by selected classification. Bureau of Labor Statistics, Washington, DC.

US Department of Labor. (1999). Proposal for an ergonomics program standard. Occupational Health and Safety Administration, Washington, DC.

VanWely P. (1970). Design and disease. *Applied Ergonomics* 1(5): 262-269.

Vessey M.P., Villard-Mackintosh L. and Yeates D. (1990). Epidemiology of carpal tunnel syndrome in women of childbearing age. Findings in a large cohort study. *International Journal of Epidemiology* 19(3): 655-659.

Viikari-Juntura E. and Silverstein B. (1999). Role of physical load factors in carpal tunnel syndrome. *Scandinavian Journal of Work Environment and Health* 25(3):163-185.

Webb Associates. (1978). Anthropometric Source Book. National Aeronautics and Space Administration, Washington, DC: IV-1 to IV-76.

Weintraub M.I. (1997). Noninvasive laser neurolysis in carpal tunnel syndrome. *Muscle and Nerve* 20(8): 1029-1031.

Weiss N.D., Gordon L., Bloom T., So Y. and Rempel D.M. (1995). Position of the wrist associated with the lowest carpal tunnel pressure: implications for splint design. *Journal of Bone and Joint Surgery* 77A: 1695-1699.

Werner R.A., Bir C. and Armstrong T.J. (1994a). Reverse Phalen's maneuver as an aid in diagnosing carpal tunnel syndrome. *Archives of Physical Medicine and Rehabilitation* 75(7): 783-786.

Werner R.A., Albers J.W., Franzblau A. and Armstrong T.J. (1994b). The relationship between body mass index and the diagnosis of carpal tunnel syndrome. *Muscle and Nerve* 17(6): 632-636.

Werner R.A. and Armstrong T.J. (1997a). Carpal tunnel syndrome: ergonomic risk factors and intracarpal canal pressures. E. W. Johnson. (Ed.) *Carpal tunnel syndrome*. W B Saunders Company, Philadelphia, PA.

Werner R.A., Franzblau A., Albers J.W., Buchele H., et al. (1997b). Use of screening nerve conduction studies for predicting future carpal tunnel syndrome. *Occupational and Environmental Medicine* 54(2): 96-100.

Williams T.M., Mackinnon S.E., Novak C.B., McCabe S., et al. (1992). Verification of the pressure provocative test in carpal tunnel syndrome. *Annals of Plastic Surgery* 29(1): 8-11.

Yassi A. (1997). Repetitive strain injuries. *The Lancet* 349: 943-947.

Yuassa J., Kishi R., Harabuchi I., Eguchi T., et al. (1996). Effects of age and skin temperature on peripheral nerve conduction velocity - a basic study for nerve conduction velocity measurement at the worksite. *Sangyo Eiseigaku Zasshi* 38(4): 158-164.

Zeiss J. and Guilliam-Haidet L. (1993). MR demonstration of a persistent median artery in carpal tunnel syndrome. *Journal of Computer Assisted Tomography* 17(3): 482-484.