

## Functional psychomotor deficits associated with carpal tunnel syndrome

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A reliable task was developed for investigating functional deficits associated with carpal tunnel syndrome (CTS). A rapid pinch and release psychomotor task utilizing muscles of the hand innervated by the median nerve was administered using a strain gauge dynamometer and providing limited force feedback. The motor performance characteristics studied were speed and force control. An experiment was conducted for studying the effects of force level, hand dominance, test-retest reliability, learning, and inter-subject variability using 13 subjects free from any hand disabilities or symptoms. A companion study was also conducted using 17 normal subjects and ten subjects diagnosed having CTS to investigate differences between CTS and control subjects. Dominant hands performed 4% to 8% better than the non-dominant hands by having a greater pinch rate, a smaller overshoot force, and less time above the upper force level and below the lower force level. Control subjects performed 25% to 82% better than CTS subjects. Age contributed 6% of the total variance for pinch rate and 7% of the total variance for the time below the lower force level. The results suggest that people suffering from CTS may experience similar functional psychomotor deficits in daily living and manual work activities.

### 1. Introduction

Carpal tunnel syndrome (CTS) is one of the most prevailing peripheral entrapment neuropathies (Phalen 1972), and is a major cause of reported occupational illness in the US (Centers for Disease Control 1989, Franklin *et al.* 1991). The symptoms of CTS are related to the motor and sensory distribution of the median nerve in the hand. The median nerve is vulnerable to compression within the rigid boundaries of the carpal tunnel (Armstrong and Chaffin 1979, Smith and Sonstegard 1977). When the wrist tendons become irritated and swollen, the resulting compression of the median nerve from the increased pressure in the bony tunnel can trap and pinch the median nerve causing occasional numbness, pain and tingling in the thumb, index and middle fingers (Phalen 1972) which impairs the sensory and motor function of the hand (Lundborg 1982).

Sensory symptoms represent the earliest and major complaint in most patients. Kendall (Kendall 1960) reported sensory changes in 86% of the CTS patients, and motor weakness in 40% of the CTS patients studied. Inglis *et al.* (1972) found 64% of the CTS patients complained of numbness, 20% of paraesthesiae, 46% of pain, and 3%

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of weakness in the hands. Functional deficits associated with CTS have been studied using clinical sensory and muscle strength tests. Methods of examining for CTS also include provocative tests such as Phalen's and Tinel's tests, and electrodiagnostic examinations.

Sensory tests can be categorized as innervation density tests and threshold tests. An innervation density test measures multiple overlapping peripheral receptive fields and the density of the innervation in the region being tested. The most common innervation density test is two-point discrimination. This test has been reliable for assessing functional nerve regeneration, but not sensitive to the gradual decrease in nerve function created by external compression (Lundborg 1982). Two-point discrimination, which is highly dependent on cortical integration, appears to remain normal even if only a few fibres conduct normally to the correct cortical end-points resulting in normal two-point discrimination for CTS (Adamson *et al.* 1971, Bell 1978, Dellon 1981, Szabo *et al.* 1984).

Threshold tests can measure a single nerve fibre innervating a single receptor or a group of receptor cells (Dellon 1981). A study introducing external compression to the median nerve at the carpal tunnel was conducted by Gelberman *et al.* (1983) using various sensory tests. The Semmes-Weinstein monofilament pressure threshold test consistently reflected gradual decreases in nerve function, using both subjective sensation and electrical testing, while the two-point discrimination innervation density test remained normal until nearly all sensory conduction had ceased. The quality of the results of these tests is highly dependent on examiner training. A vibration test that measures vibration detection threshold is becoming of increasing interest to clinicians (Jetzer 1991), but the effects of contact pressure, fatigue, and appropriate vibration stimulus waveforms for performing this test have not yet been validated clinically (Harada and Griffin 1991).

Grip strength tests have been used for evaluating recovery time after carpal tunnel release surgery (Gellman *et al.* 1989). It was suggested that this may be useful to predict when patients can return to their previous level of occupational-related activities. Having normal muscle strength is not necessarily equivalent to having normal motor function (Landsmeer 1962, Moberg 1964, Mai *et al.* 1988). Accomplishing motor tasks requires not only adequate muscle strength but also sensory input with central integration for co-ordination. Furthermore, studies have shown that at the early stages of CTS, decreased muscle strength occurred late, and not until measurable changes had already occurred in sensory function (Gelberman *et al.* 1983). Bowden and Napier (1961) generalized that the median nerve is the nerve of precision while the ulnar nerve is the nerve controlling power grip. Therefore efficient, co-ordinated use of thumb and index finger for precision activities may be significantly impaired if there is a sensory deficit, even if muscle strength is still normal.

The purpose of this study was to develop a reliable task for investigating psychomotor deficits associated with CTS. The task involved repetitively pinching and releasing a dynamometer, while providing limited force feedback. Repetitive finger exertions are often used for industrial activities such as keying switches, operating controls, and squeezing hand tools. A psychomotor task was designed for utilizing muscle groups and areas of the hand innervated by the median nerve including the index finger and thumb. The sensory and motor performance characteristics studied were speed and force control. It was hypothesized that workers suffering from CTS may experience manual performance and motor control deficits in these types of work activities.

An experiment was conducted for studying the effects of force level, hand dominance, test-retest reliability, learning, and inter-subject variability using subjects free from hand disabilities or symptoms. A comparison study was also conducted using subjects diagnosed having CTS to investigate performance differences between CTS subjects and control subjects in this task.

## 2. Method

### 2.1. Apparatus and experimental procedures

A strain gauge dynamometer containing two parallel arms was used for measuring pinch compression force (Radwin *et al.* 1992). The dynamometer was specially designed to measure force independent of the position of the index finger and thumb. This feature made it possible to accurately measure pinch force for varying hand sizes without having to adjust the instrument or restrict pinch posture. The active contact area of the dynamometer was 2.0 cm wide and 3.5 cm to 9.5 cm high from the base, which was designed to accommodate hands of a wide variety of sizes. The two dynamometer arms were mounted on a plexiglass platform and separated in order to provide a pinch span of 2.5 cm. A foam arm rest was provided for the forearms. The entire apparatus can fit easily on a small table top. The strain gauges on each arm were configured as a half-bridge using two precision ( $\pm 0.01\%$ ) resistors to complete the bridge. A Daytronic 9178 strain gauge conditioner amplified and filtered the force signal with a cut off frequency of 200 Hz. The force signal was sampled at 40 samples/s using a 12 bit analogue-digital converter (MetraByte DASH-16) and an IBM-AT microcomputer. Zero crossing times were estimated using linear interpolation between samples. The dynamometer was designed for measuring nominal exertion levels up to 200 N. Pinch force was calculated as the average force measured by the two dynamometer arms. Subjects were permitted to orient the dynamometer platform to a comfortable posture, without having flexion or extension of the wrist. The distal phalangeal pad of the index finger and thumb were placed against the two dynamometer arms while the remaining three digits were extended. The experimenter made certain that subjects used the same posture for the entire experiment.

Before participating, subjects provided informed consent (approved by the University of Wisconsin Center for Health Sciences Human Subjects Committee) and answered a brief questionnaire. The questionnaire contained some basic information, including name, gender, occupation, age, and handedness. CTS symptoms such as numbness, tingling, cold hands, or weakness were also included in the questionnaire. The questionnaire also queried if subjects had previously experienced any hand injuries or disorders including CTS, tendinitis/synovitis, Raynaud's syndrome, nerve injuries, broken bones, etc. Subjects were not recruited if they responded affirmative to any of the above symptoms or disorders.

Subjects were administered a pinch strength test for both hands to determine appropriate force levels for the experiment. The maximum voluntary contraction (MVC) level for each hand was acquired by taking the greater of two exertions of maximal effort. Each exertion lasted three seconds and the maximum force was determined from the average of the last two seconds. A 2 min rest period was provided between exertions while the contralateral hand strength was tested. Force measurements were normalized by expressing force in terms of per cent of maximal voluntary contraction (%MVC).

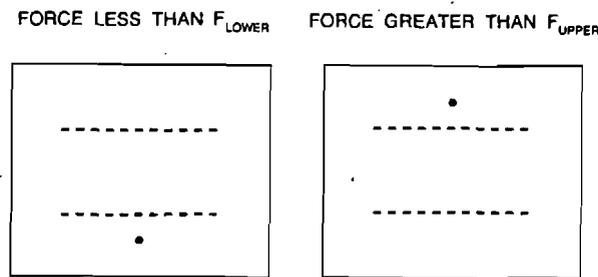


Figure 1. Visual display representing  $F_{UPPER}$  and  $F_{LOWER}$  as dotted lines and a beam that alternated positions when these force levels were crossed.

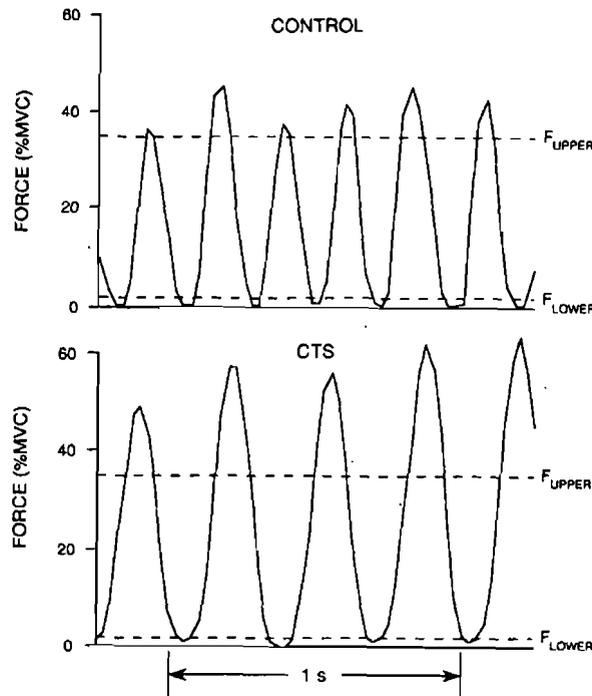


Figure 2. Plot of force against time for a selected control and CTS subject.

The psychomotor test consisted of a rapid pinch and release task. Subjects were instructed to pinch the dynamometer above an upper force level ( $F_{UPPER}$ ) and then release below a lower force level ( $F_{LOWER}$ ) as quickly as possible. Limited visual and auditory force feedback was provided. The beam on an oscilloscope display was displaced a fixed discrete vertical distance using a 12-bit digital-analogue converter. The beam discretely jumped up and a 3000 Hz tone sounded for 10 ms when the exertion level was greater than  $F_{UPPER}$  (see figure 1). After the required upper force level was achieved, any change in pinch force did not alter the visual or auditory feedback until the pinch was released below the lower force level. The beam then returned to its lower position and a 300 Hz tone sounded for 10 ms (see figure 1). Sample force records from two subjects are shown in figure 2.

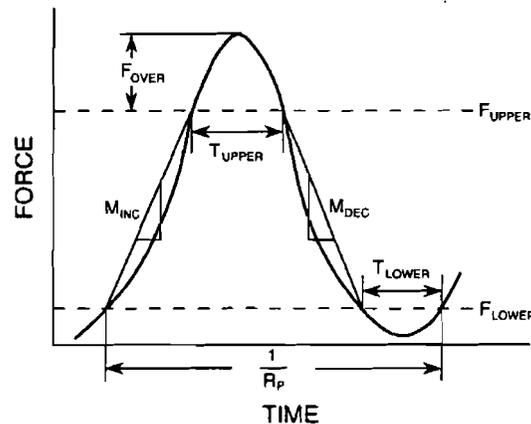


Figure 3. A representative exertion cycle indicating all performance variables.

An initial practice session was provided where the required  $F_{UPPER}$  was randomly selected from 5, 20, 35, or 50%MVC. Subjects were also allowed to practise for as long as desired prior to the beginning of every new trial. An auditory warning signal initiated a trial which lasted for 6 s, but data from the first second of the trial were considered warm-up and were ignored. Another auditory signal sounded at the end of the trial. Subjects performed the task using alternate hands and completed four conditions of  $F_{UPPER}$  (5, 20, 35, and 50%MVC) for each hand. The lower force level  $F_{LOWER}$  was fixed at 2%MVC. After finishing eight trials, subjects were provided with a 5 min rest.

A representative pinch cycle is shown in figure 3 indicating the parameters measured. A cycle starts at the point where pinch force exceeds  $F_{LOWER}$ . It is succeeded by a force that increases until  $F_{UPPER}$  is achieved or exceeded, where it rises to a peak level and then decreases when the pinch is released. Force subsequently decreases to a minimum level, equal to or less than  $F_{LOWER}$ , at which point another pinch is initiated. The cycle ends at the time when  $F_{LOWER}$  is again exceeded. A cycle is considered invalid and is not included in the analysis if an incomplete exertion occurs, such as when the peak force does not exceed  $F_{UPPER}$  or when the minimum force is greater than  $F_{LOWER}$ .

The performance variables measured for each cycle are labelled in figure 3. Pinch rate ( $R_P$ ) is defined as the inverse of the period of a cycle, in units of pinches/s. Overshoot force ( $F_{OVER}$ ) is the difference between the peak force exerted and  $F_{UPPER}$ , in terms of %MVC. Time above the upper force level ( $T_{UPPER}$ ) is the interval, in terms of ms, between the time when  $F_{UPPER}$  is exceeded for increasing pinch force, and when pinch force becomes less than  $F_{UPPER}$  for decreasing pinch force. Time below the lower force level ( $T_{LOWER}$ ) is the interval, in terms of ms, between the time when decreasing pinch force is less than  $F_{LOWER}$ , and when increasing pinch force exceeds  $F_{LOWER}$ . Increasing force slope ( $M_{INC}$ ) is the slope of the straight line between the times when  $F_{UPPER}$  and  $F_{LOWER}$  is exceeded, measured in %MVC. Similarly, the decreasing force slope ( $M_{DEC}$ ) is slope of the straight line between the time when exertion level falls below  $F_{UPPER}$  and  $F_{LOWER}$  for decreasing pinch force. The average of each performance variable for all complete exertion cycles performed in 5 s was used for the analysis.

2.1.1. *Experiment 1: Normative performance and reliability study:* This experiment was a repeated measures full factorial design. Factors included two replications (test, retest), two hands (dominant, non-dominant), and four upper force levels (5, 20, 35, and 50%MVC). The retest repeated all conditions of the experiment and was performed one week following the initial test. The lower force level was fixed at 2%MVC. Subjects alternated hands for the psychomotor task and the initial hand was counterbalanced between dominant and non-dominant hands among subjects. The four upper force levels were presented randomly and the order was independent between the two hands. Each combination of these conditions was replicated in five consecutive sets in order to study the effects of learning and fatigue.

Thirteen control subjects free of CTS symptoms were recruited for Experiment 1 by posting announcements on the University of Wisconsin–Madison campus. Subjects were paid on an hourly basis. In order to have wide range of ages, at least three subjects were recruited from each of the four age categories, (1) under 25 years, (2) 25 to 35 years, (3) 35 to 45 years, and (4) over 45 years old. Additional volunteers were not accepted after an age category was filled with four subjects. Nine females and four males participated, ranging in age between 18 and 55 years old. All subjects described themselves as right-handed.

2.1.2. *Experiment 2: Comparison between control and CTS subjects:* This experiment consisted of a repeated measures full factorial design using hand as a random effects variable nested within group, and using age as a covariate. All hands were treated as individual members in either the control or the CTS group. Factors included two levels of group (CTS, control) and four upper force levels (5, 20, 35, and 50%MVC). The lower force level  $F_{\text{LOWER}}$  was fixed at 2%MVC. CTS subjects were tested in both hands even though many of them had only one symptomatic hand. The non-symptomatic hands, however, were not regarded as normal due to the high incidence of bilateral CTS and not used for this study. Subjects alternated hands when performing the psychomotor task and the initial hand was counterbalanced among subjects. The four upper force levels  $F_{\text{UPPER}}$  were presented randomly within one hand and the order was independent between the two hands. Each combination of these conditions was replicated three times.

Ten out-patients from the University of Wisconsin Hospital and Clinics having diagnosed CTS volunteered to participate in Experiment 2. Criteria for accepting CTS subjects included CTS symptoms, based on a history and physical examination, and electrodiagnostic parameters compatible with a lesion of the median nerve in the carpal tunnel. Symptoms included paresthesias, numbness, or pain in the sensory areas of the distribution of the median nerve in the hand, occurring at night or during daily activity. Physical examination findings included hypesthesia in the median nerve distribution of the hand, or weakness in the muscles innervated by the median nerve. A positive Phalen's sign may also have been present. In all cases no evidence of history or physical examination was suggestive of another neurologic disorder such as peripheral neuropathy, radiculopathy or other nerve entrapments. Electrodiagnostic parameters were at least two standard deviations greater than normative values, including median motor latency, median antidromic sensory latency to the index finger, and median transcarpal mixed nerve latency. Needle electrode sampling did not necessarily reveal spontaneous fibrillatory activity in median nerve innervated hand musculature. In all cases nerve conduction studies of the ulnar nerve and needle electrode sampling showed no evidence of peripheral neuropathy, other focal entrapments, or radiculopathy.

There were eight female and two male patients, ranging in age between 22 and 83 years. All CTS subjects described themselves as right-handed. Four of the ten patients had bilateral CTS, which contributed 14 hands to the CTS group. In addition to using the same subjects from Experiment 1 as controls, four additional subjects were recruited into the control group in order to match the age distribution with the CTS group for Experiment 2. Twenty-six hands of the thirteen normal subjects in Experiment 1 and eight additional hands of four subjects recruited later, totalling 34 hands, were used as the control group. The CTS group consisted of 14 hands from ten patients.

### 3. Results

#### 3.1. Experiment 1: Normative performance and reliability study

Average pinch rate  $R_p$  decreased from 5.4 pinches/s (SD = 0.8) to 3.7 pinches/s (SD = 0.7) as  $F_{UPPER}$  increased from 5%MVC to 50%MVC ( $F(3,36) = 139.75$ ,  $p < 0.001$ ). The dominant hands had a statistically significant greater average  $R_p$  than the non-dominant hands ( $F(1,12) = 9.39$ ,  $p < 0.01$ ), although the difference was only 0.2 pinches/s (4%). Replication order also had a significant effect on  $R_p$  ( $F(4,68) = 6.02$ ,  $p < 0.001$ ). The Tukey studentized range test indicated that the first replicate had a smaller but statistically significant average  $R_p$  than the subsequent four replicates ( $p < 0.01$ ). The difference between the first replicate and the average of the remaining four replicates was 0.2 pinches/s (4%). The interaction between hand  $\times$  force was also statistically significant ( $p < 3,36 = 4.88$ ,  $p < 0.01$ ) (see figure 4). The difference in average  $R_p$  between the dominant hands and non-dominant hands was 0.4 pinches/s at 5%MVC, and 0.2 pinches/s at 20%MVC. No significant differences in  $R_p$  were observed between the dominant hands and non-dominant hands when  $F_{UPPER}$  was 35%MVC or 50%MVC, using a Tukey multiple contrast test ( $p > 0.05$ ). No significant  $R_p$  differences were observed between test and retest trials ( $F(1,12) = 0.42$ ,  $p > 0.5$ ).

Average overshoot force  $F_{OVER}$  was less for the dominant hands than for the non-dominant hands at a marginally significant level ( $F(1,12) = 9.11$ ,  $p < 0.05$ ). Average  $F_{OVER}$  was 11.7%MVC (SD = 4.0) for the dominant hands and 14.4%MVC (SD = 5.5) for the non-dominant hands. Replication order also had a marginally significant effect on  $F_{OVER}$  ( $F(4,48) = 5.99$ ,  $p < 0.001$ ). The Tukey studentized range test showed the first replicate had a significantly greater  $F_{OVER}$  than the subsequent four replicates ( $p < 0.05$ ). The difference between the first replicate and the average of the subsequent four replicates was 1.7%MVC. No significant effects on  $F_{OVER}$  were observed among the four upper force levels ( $F(3,36) = 1.04$ ,  $p > 0.1$ ) (see figure 5), or between test and retest trials ( $F(1,12) = 0.48$ ,  $p > 0.5$ ).

Average time above the upper force level  $T_{UPPER}$  decreased from 102 ms (SD = 26) to 68 ms (SD = 21) as  $F_{UPPER}$  increased from 5%MVC to 50%MVC ( $F(3,36) = 52.73$ ,  $p < 0.001$ ). Average  $T_{UPPER}$  at 35%MVC was 70 ms (SD = 22), which was not statistically different from  $T_{UPPER}$  at 50%MVC which was 68 ms (SD = 21), based on the Tukey contrast test ( $p > 0.05$ ). Average  $T_{UPPER}$  for the dominant hands was 7 ms less (8%) than the non-dominant hands ( $F(1,12) = 8.31$ ,  $p < 0.05$ ). The Tukey test revealed that the first replicate had a greater  $T_{UPPER}$  than the subsequent trials ( $p < 0.01$ ). The difference between the first replicate and the average of the remaining four replicates was 5 ms (6%) ( $p < 0.05$ ). No significant differences in  $T_{UPPER}$  between test and retest trials were observed ( $F(1,12) = 0.91$ ,  $p > 0.1$ ).

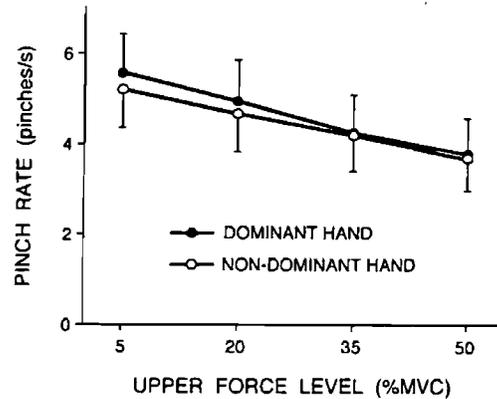


Figure 4. Plot of the interaction between hand  $\times F_{UPPER}$  for  $R_p$  (13 control subjects).

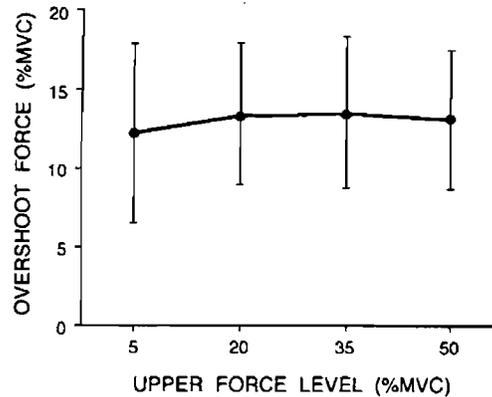


Figure 5. Plot of  $F_{OVER}$  against  $F_{UPPER}$  (13 control subjects).

Average time below the lower force level  $T_{LOWER}$  decreased when  $F_{UPPER}$  increased from 5%MVC to 50%MVC ( $F(3,36) = 14.17$ ,  $p < 0.001$ ). Average  $T_{LOWER}$  was 54 ms (SD = 17) when  $F_{UPPER}$  was 5%MVC, and decreased to 39 ms (SD = 16), and 39 ms (SD = 17) when  $F_{UPPER}$  increased from 5%MVC to 20%MVC and 35%MVC, respectively. Although the dominant hands had a smaller  $T_{LOWER}$  than for the non-dominant hands, the difference was only 3 ms (6%) ( $F(1,2) = 5.85$ ,  $p < 0.05$ ). Significant differences in  $T_{LOWER}$  between the dominant hands and non-dominant hands were observed when  $F_{UPPER}$  was 5%MVC and 20%MVC ( $p < 0.01$ ), using the Scheffé contrast test. Average  $T_{LOWER}$  was greater for the first replicate than for the remaining four replicates, as evidenced by the Tukey contrast test ( $p < 0.01$ ).  $T_{LOWER}$  for the first replicate was 5 ms greater than the average of the other replicates. No significant differences were observed between test and retest trials for  $T_{LOWER}$  ( $F(1,12) = 0.06$ ,  $p > 0.5$ ).

The average increasing force slope  $M_{INC}$  increased from 200%MVC/s (SD = 50) to 635%MVC/s (SD = 126) as  $F_{UPPER}$  increased from 5%MVC to 50%MVC ( $F(3,36) = 239.03$ ,  $p < 0.001$ ). No significant differences in  $M_{INC}$  were observed between test and retest trials ( $F(1,12) = 0.03$ ,  $p > 0.5$ ), dominant and non-dominant

hands ( $F(1,12) = 0.41$ ,  $p > 0.5$ ), or among the five replications ( $F(4,48) = 1.20$ ,  $p > 0.5$ ).

The magnitude of the average decreasing force slope  $M_{DEC}$  increased from 172%MVC/s ( $Sd = 39$ ) to 544%MVC/s ( $Sd = 97$ ) as  $F_{UPPER}$  increased from 5%MVC to 50%MVC ( $F(3,36) = 295.27$ ,  $p < 0.001$ ). No significant differences in  $M_{DEC}$  were observed between test and retest trials ( $F(1,12) = 0.02$ ,  $p > 0.5$ ), dominant and non-dominant hands ( $F(1,12) = 3.45$ , ( $p > 0.1$ ), or among the five replications ( $F(4,48) = 0.18$ ,  $p > 0.5$ ).

### 3.2. Experiment 2: Comparison between control and CTS subjects

The average pinch strength for the control subjects was 41.7 N ( $SD = 14.5$ ). The maximum control subject strength was 74.1 N and the minimum strength was 18.4 N. The average pinch strength for the CTS subjects was 34.1 N ( $SD = 13.6$ ). The maximum strength was 62.1 N and the minimum strength was 11.3 N for the CTS subjects. The difference in average pinch strength between control and CTS subjects was not statistically significant ( $F(1,46) = 2.85$ ,  $p > 0.05$ ).

Since the results of Experiment 1 indicated that the first replicate was the only replicate significantly different from the others, the first replicate was used as a warm-up trial for each of the subsequent conditions in Experiment 2. Data from the second and third replicants for control subjects in Experiment 1 were then retained for Experiment 2.

Average pinch rate  $R_P$  was 0.9 pinches/s greater (25%) for the control subjects than for the CTS subjects ( $F(1,45) = 10.04$ ,  $p < 0.01$ ). There was also a significant interaction between force  $\times$  subjects for  $R_P$  ( $F(3,138) = 10.07$ ,  $p < 0.001$ ) (see figure 6). The Tukey test indicated the differences in  $R_P$  between CTS subjects and control subjects was not significant when  $F_{UPPER}$  was 50%MVC ( $p > 0.05$ ). There was also no significant difference in  $R_P$  between  $F_{UPPER}$  for 5%MVC and 20%MVC, or between 35%MVC and 50%MVC ( $p > 0.05$ ) for the CTS subjects. The age covariate had a significant effect on  $R_P$  ( $F(1,45) = 5.34$ ,  $p < 0.05$ ). The effect of age for  $R_P$ , however, only contributed 6% to the total variance.

Average overshoot force  $F_{OVER}$  was 11.5%MVC greater (82%) for the CTS subjects than for the control subjects ( $F(1,45) = 18.48$ ,  $p < 0.001$ ) (see figure 7). No significant age effect was observed for  $F_{OVER}$  in the covariance analysis ( $F(1,45) = 1.15$ ,  $p > 0.1$ ).

Average time above the upper force level  $T_{UPPER}$  was 41 ms greater (51%) for the CTS subjects than for the control subjects ( $F(1,45) = 17.37$ ,  $p < 0.001$ ). No significant age effect was observed for  $T_{UPPER}$  in the covariance analysis ( $F(1,45) = 2.48$ ,  $p > 0.1$ ). Average time below the lower force level  $T_{LOWER}$  for the CTS subjects was 23 ms greater (60%) than for control subjects ( $F(1,45) = 13.67$ ,  $p < 0.001$ ). The age covariate did have a significant effect on  $T_{LOWER}$  ( $F(1,45) = 8.04$ ,  $p < 0.01$ ). The effect of age for  $T_{LOWER}$  only contributed 7% of the total variance. No significant differences were observed in the average increasing force slope  $M_{INC}$  ( $F(1,46) = 1.49$ ,  $p > 0.05$ ) or in the average decreasing force slope  $M_{DEC}$  ( $F(1,46) = 3.12$ ,  $p > 0.05$ ) between the CTS subjects and the control subjects.

Among the four performance variables  $R_P$ ,  $F_{OVER}$ ,  $T_{UPPER}$ , and  $T_{LOWER}$ , that showed significant differences between CTS subjects and control subjects,  $F_{OVER}$  had the greatest magnitude difference (82%) and  $R_P$  had the smallest (25%). The variable  $R_P$ , however, had the smallest coefficient of variance (0.18) while  $F_{OVER}$  had the largest (0.42). The Pearson correlation matrix showed  $R_P$  was negatively correlated

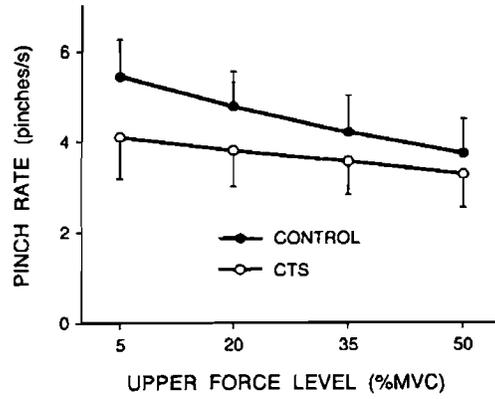


Figure 6. Plot of the interaction between group  $\times F_{UPPER}$  for  $R_p$ .

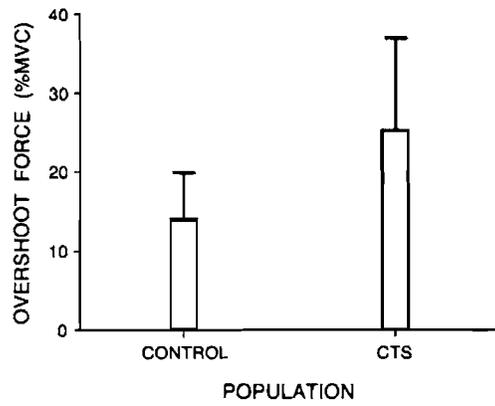


Figure 7. Comparison of  $F_{OVER}$  between control and CTS subjects.

Table 1. Pearson correlation of performance variables (13 control subjects).

Variable	$R_p$	$F_{OVER}$	$T_{UPPER}$	$T_{LOWER}$	$M_{INC}$
$F_{OVER}$	- 0.331				
$T_{UPPER}$	- 0.849***	0.728**			
$T_{LOWER}$	- 0.672**	0.067	0.398		
$M_{INC}$	0.279**	0.110	- 0.555*	- 0.191	
$M_{DEC}$	0.840***	0.073	- 0.595*	- 0.195	0.940***

\*  $p < 0.05$ .  
 \*\*  $p < 0.01$ .  
 \*\*\*  $p < 0.001$ .

with  $T_{\text{UPPER}}$  ( $r = -0.849$ ,  $p < 0.001$ ) and  $T_{\text{LOWER}}$  ( $r = 0.729$ ,  $p < 0.01$ ) (see table 1).  $F_{\text{OVER}}$  was correlated with  $T_{\text{UPPER}}$  ( $r = -0.728$ ,  $p < 0.01$ ). The variable  $R_{\text{P}}$  had the lowest correlation with the variable  $F_{\text{OVER}}$  (see table 1).

#### 4. Discussion

The CTS subjects not only had a 25% smaller average  $R_{\text{P}}$  than the control subjects, but the effect of  $F_{\text{UPPER}}$  on  $R_{\text{P}}$  was not as large for the CTS subjects as for the control subjects (see figure 7). This suggested that the control subjects were capable of sensing changes in  $F_{\text{UPPER}}$  and reacting to it when performing the rapid pinch and release task while the CTS subjects were not. It was also suggested that the low  $F_{\text{UPPER}}$  was more sensitive in differentiating these two groups than the high  $F_{\text{UPPER}}$  since no significant difference in  $R_{\text{P}}$  between the CTS subjects and the control subjects was observed when  $F_{\text{UPPER}}$  was 50%MVC, but  $R_{\text{P}}$  had the greatest differences when  $F_{\text{UPPER}}$  was at 5%MVC. Average  $R_{\text{P}}$  decreased from 5.4 pinches/s to 3.7 pinches/s (31%) as  $F_{\text{UPPER}}$  increased from 5%MVC to 50%MVC for the control subjects. CTS subjects, on the other hand, had only a small decrease in  $R_{\text{P}}$  from 4.1 pinches/s to 3.3 pinches/s as  $F_{\text{UPPER}}$  increased from 5%MVC to 50%MVC. One possible explanation is that CTS subjects had sensory feedback deficits due to the injured median nerve resulting in these motor control deficits. Another explanation is that motor neurons of the median nerve were injured. These motor deficits may have prevented CTS subjects from reacting to the changes in  $F_{\text{UPPER}}$ , regardless of the state of their sensory function. It is also possible that very rapid  $R_{\text{P}}$  for small  $F_{\text{UPPER}}$  levels requires intact sensory and/or motor function while less optimal sensory and/or motor function is required for greater  $F_{\text{UPPER}}$  levels.

The age range for the CTS subjects in this study was between 22 to 83 years. The age for the control subjects overlapped the CTS subjects, ranging from 18 to 82 years. Since age may be an essential factor when dealing with sensory or motor function, it was necessary to ensure that the performance differences observed between the two samples were not confounded with age. Therefore the statistical model in the present study used age as a covariate in order to account for possible confounding age effects. Age was statistically significant for  $R_{\text{P}}$  and  $T_{\text{LOWER}}$ , which lead to a more detailed *post hoc* analysis. The effect of age for  $R_{\text{P}}$  contributed 6% of total variance and for  $T_{\text{LOWER}}$  contributed 7% of the total variance. A linear regression model using group and age as the independent variables and pinch rate as the dependent variable showed  $R_{\text{P}} = 5.16 - 0.66 \times G - 0.02 \times A$  ( $R^2 = 0.256$ ,  $p < 0.001$ ). The group variable was  $G = 0$  for the control subjects and  $G = 1$  for the CTS subjects, and Age ( $A$ ) was in years. The standardized regression coefficient was  $-0.351$  for group and  $-0.306$  for age. The regression model for time below the lower force level was  $T_{\text{LOWER}} = 27.7 + 18.0 \times G + 0.4 \times A$  ( $R^2 = 0.332$ ,  $p < 0.001$ ). The standardized regression coefficient was 0.395 for group and 0.353 for age.

$F_{\text{OVER}}$  was 82% greater for the CTS subjects than for the control subjects. This may have been the result of impaired proprioceptive or mechanoreceptor afferent nerve fibres of the median nerve. A recent study (Radwin *et al.* 1991) indicated that functional tactility deficits were associated with CTS in a ridge detection task. Workers having CTS may face a higher exposure to forceful exertions when performing repetitive pinch tasks since they tended to exert more force than the minimum force required. Forceful exertions had long been regarded as a risk factor to cumulative trauma disorders (Armstrong and Chaffin 1979, Putz-Anderson 1988).

The CTS subjects had a 51% longer  $T_{\text{UPPER}}$  and 60% longer  $T_{\text{LOWER}}$  than the control subjects which might indicate that CTS is associated with difficulties releasing and

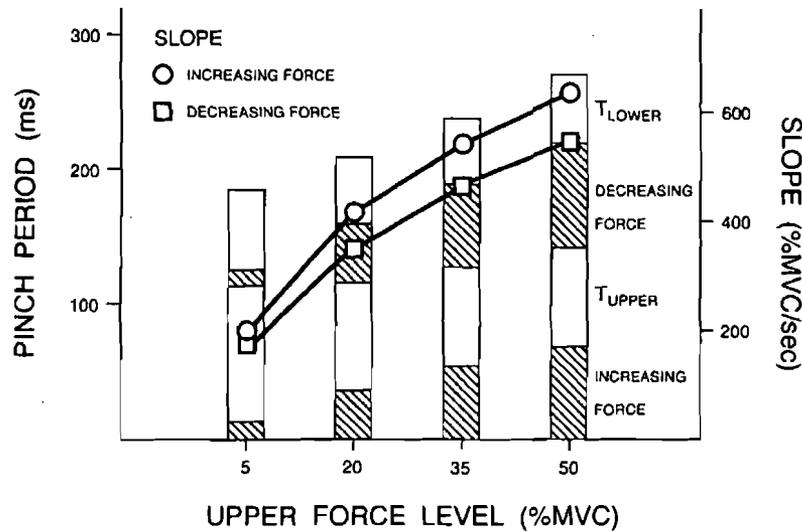


Figure 8. Average pinch cycle period plotted against  $F_{UPPER}$ . The average pinch period was computed using the sum of the time for increasing force,  $T_{UPPER}$ , and decreasing force,  $T_{LOWER}$ .

Table 2. Test-retest reliability of performance variables (13 control subjects).

Variable	Pearson correlation coefficient
$R_p$	0.895***
$F_{OVER}$	0.559*
$T_{UPPER}$	0.819***
$T_{LOWER}$	0.953***
$M_{INC}$	0.768**
$M_{DEC}$	0.706**

\*  $p < 0.05$ .

\*\*  $p < 0.01$ .

\*\*\*  $p < 0.001$ .

reinitiating repetitive pinch exertions. These functional difficulties may be caused by impairments of both sensory and motor fibres of the median nerve. Future work will investigate motor and sensory differences using nerve conduction studies (Rodriguez et al. 1993).

The observation that average pinch rate  $R_p$  decreases with increasing  $F_{UPPER}$  indicates a longer pinch duration is required for higher  $F_{UPPER}$  levels. Average overshoot force  $F_{OVER}$ , did not change for increasing  $F_{UPPER}$  levels. As  $F_{UPPER}$  increased from 5%MVC to 50%MVC, average  $R_p$  decreased as much as 1.7 pinches/s, while average  $F_{OVER}$  did not change. This indicates that task performance requiring repetitive finger exertions can be maximized by minimizing force requirements without risking greater overshoot forces at lower force levels. This has particular application in keyboard design and control of activation force for tools and controls.

The overall pinch cycle period for each  $F_{UPPER}$  can be estimated using the sum of the average increasing force time, the time above  $F_{UPPER}$ , decreasing force time, and the time below  $F_{LOWER}$  (see figure 8). The increasing force time was derived from

the increasing slope  $M_{INC}$  and the incremental  $F_{UPPER}$  force level. The decreasing force time was similarly derived from the decreasing slope  $M_{DEC}$  and the decremental  $F_{UPPER}$  force level. The slopes were the average  $M_{INC}$  and average  $M_{DEC}$  at each  $F_{UPPER}$ . It was observed that the slopes  $M_{INC}$  and  $M_{DEC}$  increased three fold as  $F_{UPPER}$  increased from 5%MVC to 50%MVC. The difference between  $F_{UPPER}$  and  $F_{LOWER}$  was 15 times greater for the 50%MVC upper force level than for the 5%MVC upper force level. Therefore the incremental increase of  $M_{INC}$  and  $M_{DEC}$  was less than the incremental increase in the required pinch force. Hence the time for the increasing and decreasing force phases increased as  $F_{UPPER}$  increased. The consequence was that  $R_P$ , which was the reciprocal of pinch period, decreased as  $F_{UPPER}$  increased. This decrease was apparently covered by the increase in slope (see figure 8).

The dominant hands performed better than the non-dominant hands for  $R_P$ ,  $F_{OVER}$ ,  $T_{UPPER}$ , and  $T_{LOWER}$ , which agreed with numerous studies involving performance differences associated with hand dominance (Peters and Durding 1979, Podbros and Wyke 1988, Shimoyama *et al.* 1990). The better performance of the dominant hands (4% to 8%) indicated that the pinch and release task was somewhat sensitive to these differences, although the effect is small. The effect of hand dominance was much less than the effect of CTS. Since there were more dominant hands than non-dominant hands included in the CTS group (10 dominant vs. 4 non-dominant) and an equal number of dominant and non-dominant hands in the central group (17 dominant vs. 17 non-dominant), the likelihood of handedness differences being confounded for observed performance differences in  $R_P$ ,  $F_{OVER}$ ,  $T_{UPPER}$ , and  $T_{LOWER}$  was unlikely.

The significant differences between the first replicate and the subsequent four replicates in Experiment 1 for most performance variables ( $R_P$ ,  $F_{OVER}$ ,  $T_{UPPER}$ , and  $T_{LOWER}$ ) indicated a rapid learning process existed at the beginning of this psychomotor task. The absence of significant differences after the second replicate means the subjects can perform this task without requiring much practice. This is a desired feature of experimental and clinical tests since it does not take excessive training time to starting to collect reliable data. It is not only desirable in terms of time savings, but also in terms of maintaining motivation and vigilance levels.

No significant differences were observed between test and retest trials for all of the performance variables in this task. High correlations between test and retest trials on the performance variables suggests that this test is reliable (see table 2). Since the results from the retest trial was not different from the test trial, the retest trial was not executed for the CTS subjects in Experiment 2.

The time to run Experiment 2 for one subject was less than 45 min, which included signing consent forms, answering a symptom questionnaire, practice trials, three replications, and 5 min rest periods between replications. Since the results indicated that CTS subjects and control subjects had the greatest performance differences when  $F_{UPPER}$  was 5%MVC, it may be possible to execute the task for only  $F_{UPPER}$  at 5%MVC in 15 min without losing sensitivity of the test.

Even though the rapid pinch task was designed for performing at isometric contraction levels, subjects still had some degree of finger movement. It would have been better if extraneous movements were controlled as much as possible. In order to more carefully study the consequences of an injured median nerve, the muscles innervated by other nerves of the hand, such as radial nerve or ulnar nerve, should be isolated from thumb movements controlled by the thenar muscles. A substitution pattern could occur where the same function is accomplished using different muscles than would normally be used for that activity. These substitution patterns will be

controlled in future studies by imposing postural constraints in order to evaluate more accurately motor deficits of the median nerve.

### 5. Conclusions

This study showed that pinch rate decreased with increasing upper force level, whereas overshoot force did not change. The dominant hands performed 4% to 8% better than the non-dominant hands for  $R_P$ ,  $F_{OVER}$ ,  $T_{UPPER}$ , and  $T_{LOWER}$ . The control subjects performed 24% to 82% better than CTS subjects. This suggests that similar functional psychomotor control deficits in daily living and manual work activities can occur for CTS. Correlation indicated that performance variables  $R_P$  and  $F_{OVER}$  were independent and should both be reported when using this test. The test developed had high test-retest reliability. Subjects performed the task without requiring much practice, and the time to run the test could be minimized to as little as 15 min. The entire apparatus to run the test can fit easily on a small table top. Future work will try to differentiate motor and sensory deficits in CTS using this psychomotor test and nerve conduction studies.

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