Published in final edited form as:

Clin Neurophysiol. 2012 November ; 123(11): 2281–2290. doi:10.1016/j.clinph.2012.04.013.

Effects of Carpal Tunnel Syndrome on adaptation of multi-digit forces to object texture

Mostafa Afifi¹, Marco Santello³, and Jamie A. Johnston^{1,2}

¹Faculty of Kinesiology, University of Calgary, Calgary, AB T2N 1N4, Canada

²Hotchkiss Brain Institute, University of Calgary, Calgary, AB T2N 1N4, Canada

³School of Biological and Health Systems Engineering, Arizona State University, Tempe, AZ 85287, USA

Abstract

Objective—The ability to adapt digit forces to object properties requires both anticipatory and feedback-driven control mechanisms which can be disrupted in individuals with a compromised sensorimotor system. Carpal Tunnel Syndrome (CTS) is a median nerve compression neuropathy affecting sensory and motor function in a subset of digits in the hand. Our objective was to examine how CTS patients coordinate anticipatory and feedback-driven control for multi-digit grip force adaptation.

Methods—We asked CTS patients and healthy controls to grasp, lift, and hold an object with different textures.

Results—CTS patients effectively adapted their digit forces to changes in object texture, but produced excessive grip forces. CTS patients also produced larger peak force rate profiles with fewer modulations of normal force prior to lift onset than did controls and continued to increase grip force throughout the lift whereas forces were set at lift onset for the controls.

Conclusions—These findings suggest that CTS patients use less online sensory feedback for fine-tuning their grip forces, relying more on anticipatory control than do healthy controls.

Significance—These characteristics in force adaptation in CTS patients indicate impaired sensorimotor control which leads to excessive grip forces with the potential to further exacerbate their median nerve compression.

Keywords

Carpal Tunnel Syndrome; sensorimotor processes; texture; manipulation

Introduction

Healthy individuals effectively and efficiently adapt digit forces to object properties through anticipatory and feedback-driven control mechanisms (Johansson, 1996, 1998; Johansson

© 2012 International Federation of Clinical Neurophysiology. Published by Elsevier Ireland Ltd. All rights reserved.

Address for correspondence: Jamie A. Johnston, Faculty of Kinesiology, Kinesiology Building B 420, University of Calgary, Calgary, AB, Canada T3K 5H4, Ph.: +1-403-220-3649, Fax: +1-403-284-3553, johnston@kin.ucalgary.ca.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

and Westling, 1984, 1987, 1988a,b; Rearick and Santello, 2002; Reilmann et al., 2001; Salimi et al., 2003; Westling and Johansson, 1984). This sensorimotor adaptation relies on the ability to effectively integrate somatosensory feedback about object properties with the motor commands for digit force modulation. For example, when lifting a glass of water, properties such as center of mass, weight, and texture need to be accurately sensed by the hand (feedback control) to distribute digit forces such that the glass neither slips, tilts, nor crushes. When grasping this same glass of water multiple times, the digit forces necessary for doing so effectively are anticipated and programmed in advance of the lift (anticipatory control).

These sensorimotor processes are often disrupted in clinical populations leading to less effective and less efficient force control (Gordon et al., 2006; Santello et al., 2004; Zhang et al., 2011). One condition that specifically affects the hand is carpal tunnel syndrome (CTS), a compression neuropathy of the median nerve producing sensory deficits in the thumb, index, middle, and radial half of the ring finger and, in more severe cases, motor deficits primarily affecting the thenar muscles. The extent of injury to the median nerve is quantified by reductions in the conduction velocity and/or amplitude of the median nerve sensory or motor evoked potentials across the wrist (Hilburn, 1996; Jablecki et al., 1993; Kimura, 2001; Oh, 2003). However, the functional significance of these measures of nerve conduction, i.e., how median nerve injury and thus CTS, affects somatosensory detection, discrimination and the integration of sensory and motor function necessary for adapting to environmental demands, continue to be debated (D'Arcy and McGee, 2000; Franzblau et al., 1994; Johnston and Santello, 2009; King, 1997; Thonnard et al., 1999; Werner et al., 1994, 1995; You et al., 1999; Zhang et al., 2011).

Studies of CTS patients (Thonnard et al., 1999) and mechanically-induced median nerve compression (Cole et al., 2003) on two-digit grasping have shown effective force adaptation to object texture, but the use of inefficient grip forces that exceed those necessary for holding the object. This latter observation points to impairments in the sensorimotor processes underlying force control in CTS patients. However, the effects of CTS on patients' ability to coordinate anticipatory and feedback control in whole-hand object manipulation have not been thoroughly examined. Fully understanding these sensorimotor processes requires examining grip force changes that occur both *within* as well as *across* multiple interactions with a given object. Thus, the first objective of the current study was to characterize sensorimotor processes underlying grip force control and adaptation to texture in CTS patients.

A second objective was to examine these processes in CTS patients during a five-digit grasping task. With the exception of a recent study by Zhang et al. (2011), all the studies on the effects of median nerve impairment on force adaptation were performed using tasks performed by only the median-innervated thumb and index finger. As CTS selectively impairs sensorimotor function at a subset of digits, the examination of grip force adaptation in CTS affords unique opportunities for understanding how the Central Nervous System integrates sensory information from CTS-affected and non-affected digits with motor commands to fine-tune digit forces to object properties.

To address these objectives, we asked subjects to lift an object with differing textures using all five digits and examined the digit forces produced both within and across trials. We hypothesized that CTS patients would (1) be capable of adapting their digit forces to changes in object textures, but would (2) use greater than needed grip forces, and (3) exhibit a reduced number of online force modulations revealing an imbalance between the use of anticipatory and feedback-driven control. Preliminary results of this study have been published in abstract form (Afifi et al., 2011).

Methods

Subjects

Eleven individuals diagnosed with CTS (2 males and 9 females, aged 49.1 ± 8.9 years) and eleven age- and gender-matched healthy controls (aged 49.8 ± 8.8 years; matching age criteria: ± 2 years) participated in this study. The diagnosis of CTS was verified by nerve conduction tests (NCTs; see Table 1), considered the best available diagnostic standard (De Krom et al., 1990; Gunnarson et al., 1997; Jablecki et al., 2002), conducted at one of two Calgary hospitals. Inclusion criteria were 1) a prolonged distal sensory latency (antidromic or orthodromic, relative or absolute) or sensory nerve action potential (SNAP) amplitude below the lower limit of normative values (Table 2) and 2) ulnar nerve recordings (sensory and motor) within normative values. Control subjects did not receive NCTs (see below).

Patients and controls also underwent tactile sensory perception (Semmes-Weinstein monofilaments) and median nerve provocative tests (Durkan's nerve compression, Phalen's, and Tinel's tests). All provocative tests were considered positive if the subject experienced pain, numbness, and/or tingling in any of the radial three and half fingers of the palmar aspect of the hand (see Table 3 for results). Controls were excluded from the study if any of these tests were positive or they showed less than perfect tactile sensation in any digit. Further exclusion criteria for either group was: (1) history of musculoskeletal or neurological disorders (other than CTS for the patient group), (2) diabetes, (3) uncorrected vision problems, (4) significant stiffness/rigidity, (5) unmedicated thyroid disorders, (6) history of hand surgical interventions or corticosteroid injections for CTS, (7) pregnancy, (8) tremor in the fingers or hands, or 9) arthritis in the upper extremity. All subjects were naive to the experimental purpose of the study and gave informed consent in accordance with the Declaration of Helsinki prior to participating in the experiment. The experimental procedures were approved by the Conjoint Health Research Ethics Board at the University of Calgary.

Subject Characteristics

The diagnosis of CTS was confirmed in all patients (Table 1) through NCTs performed on average ($\pm$ SD) 49 ± 36 days prior to participating in our study. All of the patients were diagnosed with CTS in both hands resulting in the collection of data from the hand considered to be the more severely affected of the two by the attending neurologist. The sensory and provocative tests (Table 3) revealed significant variability across the patient group in tactile sensitivity and provocative signs of CTS.

Experimental apparatus

Forces and torques exerted by all digits during the grasping task (see below) were measured by five force/torque (F/T) transducers (ATI Industries, Garner, NC; Nano-17 for the fingers and Nano-25 for the thumb; force and torque measurement resolutions: 0.00625 N and 0.03125 N·mm, respectively, for Nano-17 and 0.0625 N and 0.379 N·mm, respectively for Nano-25). The F/T sensors were mounted on a grip device (see Fig. 1) such that the center of the thumb sensor was aligned opposite the midpoint between the middle and ring finger sensors and the grip width was 8.7 cm. The signals from each sensor were acquired by a 12-bit A/D converter board (an 80-channel M-series DAQ 6255 board, National Instruments, Austin, TX) at a sampling frequency of 1 kHz. Custom software (LabVIEW 7.1, National Instruments, Austin, TX) was used to acquire, display, and store the force data for offline analysis.

Experimental task

Prior to data collection, participants washed their hands with soap and warm water to remove any oils from the skin. The apparatus was placed on a table at a comfortable distance from the hand being tested. Each CTS patient used his/her most affected hand while his/her control used the hand corresponding to that used by the patient. The subject sat on a height-adjustable chair with the wrist resting comfortably on the table. After a verbal command “ready”, subjects positioned their hand in a grasping position around the device, without touching it, to facilitate proper digit placement on the sensors. This was immediately followed by the verbal command “lift” after which they grasped and lifted the device approximately 5–10 cm above the table using the fingertips of all five digits. Subjects were instructed to lift the object “as if they were lifting a glass of water” thus requiring sub-maximal force production. Subjects were also told to maintain the device vertical, assisted visually by a bubble level placed on top of the apparatus (Fig. 1), and to keep their entire upper arm off the table throughout the lift and hold. After holding the object for about 6 s, subjects were verbally instructed to “replace” the object back on the table. The same verbal instructions were used for all conditions and for every trial. Note that none of our participants, the CTS patients or controls, dropped the device (Pazzaglia et al., 2010).

To assess the extent to which patients with CTS could utilize both anticipatory and feedback-driven control to generate appropriate multi-digit forces as a function of texture, we changed object texture using a *blocked design*. Specifically, subjects performed two blocks of 12 consecutive lifting trials. Between blocks, we changed the texture of each of the digit-object contact points by attaching caps covered with either silk or sandpaper (static coefficient of frictions: 0.39 and 1.46, respectively; see Aoki et al., 2007) to each F/T sensor. We used the same black color for each texture and dimmed the lights to prevent subjects from observing the object’s texture. Hence, actual texture could only be sensed through tactile input once contact was made with the object. The order of texture presentation was counterbalanced across subjects. None of our subjects complained of fatigue or pain during or after the experiment.

Data processing

The force data were first subdivided into three grip phases (Fig. 2A), i.e., force rise, lift, and hold, each of which are delineated by different mechanical events that must be sensed by the appropriate receptors within the somatosensory system of the hand for efficient and effective object manipulation (Johansson and Flanagan, 2009). The force rise phase was the time period between when the last digit contacted the object and lift onset within which normal and tangential forces gradually increase until the object is accelerated vertically. Force rise onset was defined as the time at which the last digit contacted the force sensors and produced enough normal force to exceed a 0.1 N threshold (Raghavan et al., 2006; Rao et al., 2011) for 1 s. The end of the force rise phase was marked by lift onset, determined as the time at which the total tangential force (sum of all digit tangential forces, ΣF_T ; Fig. 2B) exceeded the weight of the object (5.44 N). The force rise phase of the grasp is critically important for determining force adaptations to texture, as texture changes can be sensed at the fingertips upon first digit contact. For this reason, we further divided the force rise phase into the preload phase, defined as the time from force rise onset to the time at which ΣF_T last crossed 0 N while increasing (load onset; see Fig. 2B), and load phase (Forssberg et al., 1991; Johansson and Westling, 1984; Rearick et al., 2003) which was delimited by load and lift onsets.

The lift phase was the time between when the object left the table and the object was held stationary against gravity. Lift onset (see above) marks the beginning of the lift phase, whereas hold onset, determined as the time at which the first derivative of ΣF_T crossed zero

after lift onset (Fig. 2C), marked the termination of the lift phase. For analysis purposes, the hold phase was defined as the 2-s time period between 2 and 4 s after hold onset to capture the most stable period of the hold.

After subdividing the force data into the above-described epochs, the following variables were computed to examine how CTS and control subjects adapted multi-digit forces to object texture. First, as the median nerve innervates the radial three and half digits and force adjustments to texture in healthy individuals occur approximately 150 ms after object contact (Johansson and Westling, 1984), it was important to identify the digit contact and timing strategies for each group. Thus we determined (1) the number of times each digit was the first to make contact with the device, (2) the time between the first and last digit to make contact with the device (digit contact time) and (3) preload phase duration to determine whether these times were sufficient for sensing and perceiving object texture. Second, we examined how the five digits worked in concert by computing the sum of the five digits' normal forces (ΣF_n) at load, lift, and hold onsets and determining the mean ΣF_n over the 2-s hold phase. Next, the first and second time derivatives of ΣF_n were determined for the force rise phase. From these measures, the peak ΣF_n rate (Forssberg et al., 1991; Gordon et al., 1997, 2000; Johansson and Cole, 1992; Rearick et al., 2003; Winstein et al., 1991) and ΣF_n modulations within each trial were determined. Within-trial force modulations were recorded as the number of zero crossings in the second time derivative. Lastly, we quantified the extent to which digit forces were controlled independently by examining how the forces were shared among the four fingers opposing the thumb. Thus, we determined the digit force sharing pattern by normalizing the normal force exerted by each finger to that produced by the thumb at load, lift, and hold onsets as well as during the hold phase.

Statistical analysis

To determine differences in the ability of CTS patients and controls to adapt to object texture, 2×2 ANOVAs with repeated measures were used with the between-subjects factor, Group (CTS patients vs. controls), and within-subjects factor, Texture (sandpaper vs. silk). The ANOVAs were conducted on the following dependent measures: (a) preload duration, (b) digit contact time, (c) ΣF_n , run separately for load, lift, and hold onsets, as well as mean hold, (d) peak ΣF_n rate, and (e) ΣF_n modulations. For all these measures, the first two trials in each block were removed as "learning" trials and the last ten trials were averaged and analyzed.

To determine differences in force adaptations occurring across trials, $2 \times 2 \times 3$ ANOVAs with repeated measures were conducted on all the aforementioned dependent variables using the between-subjects factor, Group, and within-subjects factors, Texture and Trial (1st, 2nd, average trials 3–12). Given the significant results of this analysis and to elucidate further force adaptation to texture, we performed additional analysis on Trial 1 alone. Trial one is critical for understanding anticipatory vs. feedback control as the new texture is first introduced to the subject in this trial. Thus, we performed 2×2 ANOVAs with repeated measures with the between-subjects factor, Group, and within-subjects factor, Texture, on the dependent measures of ΣF_n load onset, peak ΣF_n rate, and ΣF_n modulation for Trial 1.

In addition, a series of $2 \times 2 \times 4$ ANOVAs with repeated measures were conducted to determine differences in force sharing patterns at load, lift, and hold onsets as well as mean hold with the between-subjects factor, Group, and within-subjects factors, Texture and Digit (index, middle, ring, little). However, as no Group differences were observed at any time point, force sharing patterns will not be discussed further. Lastly, to determine whether the count distributions of digits first contacting the device differed across groups and texture conditions (4 distributions), χ^2 tests were performed. When appropriate, Mauchly's test was used to test for sphericity and when violated a Greenhouse-Geisser correction was used. Post

hoc comparisons were performed using a Bonferonni adjustment. A significance level of $P < 0.05$ was used for all comparisons.

Results

Normal force production across grip phases

Figure 3A shows ΣF_n averaged across the last 10 trials produced by all CTS patients and controls during both texture conditions and at different points in the grasp, i.e., at load, lift, and hold onsets, as well as, mean hold. Our statistical analysis indicated that both subject groups produced significantly more ΣF_n during the silk texture condition at all time points in the grasp (see Table 4 for all statistical results). While there was no difference in ΣF_n between Groups for any of these events (Fig. 3A), we noted a differential effect of aging on the force produced by the healthy controls vs. CTS patients. Thus, we divided the participants into older (≥ 58 years, $n = 3$) and younger (≤ 57 years, $n = 8$) age groups and compared the ΣF_n between the controls and CTS patients within each group. In the younger age group (Fig. 3B), CTS patients exhibited greater ΣF_n than controls for both texture conditions at lift onset, hold onset, and mean hold. Note that the group difference in ΣF_n at load onset followed the same trend, but was not statistically significant ($P = 0.059$). Analysis also revealed larger grip forces for the silk vs. the sandpaper conditions at load, lift and hold onsets as well as mean hold. Thus, younger CTS patients successfully adapted their normal forces to texture after the first few trials and did so early in the grasp, but generally with larger forces than controls.

Figure 3B also shows the within-trial evolution of the ΣF_n occurring during the lift and hold grasp task. Control subjects showed a fairly consistent ΣF_n from lift onset through to mean hold, whereas the CTS patients continued to increase their ΣF_n from lift to hold onset. Thus, the difference in ΣF_n between lift and hold onset was computed and a repeated measures ANOVA was run examining the same independent measures (Texture and Group) on this difference. This analysis confirmed that the difference between lift and hold onsets were significantly greater for younger CTS patients compared to their controls with no significant Texture differences or interactions.

The forces in the older age group (Fig. 3C) showed the opposite trends. Specifically, controls showed greater ΣF_n than did the CTS patients. Moreover, the control subjects in this age group did not appear to modify their forces to texture, having nearly identical ΣF_n for both sandpaper and silk, whereas the CTS patients had an observable difference in ΣF_n between each texture. Note that statistical analysis was not performed given the small number of subjects in the older group ($n=3$). However, through observation we noticed that older participants showed the opposite results for all of the outcome measures except the preload duration, for which they showed no difference. Furthermore, there were no clear differences in the electrodiagnostic, tactile sensory perception, or provocative tests between the younger and older groups. However, given the known differences in grasping with age (see below), limited number of older participants, and the fact that we are not studying the effects of aging, all further analyses presented in this paper will be that of the younger individuals only.

Analysis of the across-trial evolution of ΣF_n in the younger individuals revealed a significant main effect of Trial for the load (Fig. 4), lift, and hold onsets with no significant differences in mean hold nor any interactions. Post-hoc analysis indicated that there was significantly greater normal force for (1) Trial 1 vs. the Average (trials 3–12; see above) for the load and lift onsets ($P < 0.05$) and (2) Trials 1 and 2 vs. the Average ($P < 0.05$) for hold onset in both CTS patients and controls. Furthermore, there was a main effect of Texture across trials with greater ΣF_n during the silk condition at all time points. This suggests that texture adaptations

emerge early in the grasp on Trial one when the new texture is first introduced (Fig. 4). Thus, we examined the differences in the digit normal forces at load onset in Trial one alone. This analysis revealed a significant difference between textures at load onset in both CTS patients and controls.

Normal force rate and modulations

Figures 5A-D show ΣF_n rates and second derivatives produced during the force rise phase across all sandpaper trials of a representative CTS patient (No. 1) and her healthy control. These figures show that this CTS patient produced a higher peak ΣF_n rate than did the control subject (Figs. 5A vs. B). Furthermore, the CTS patient produced single peaked ΣF_n rate patterns which were bell shaped and encompassed the entire force rise phase (Fig. 5A). Conversely, the control subject produced multi-modal ΣF_n rate profiles with continued modulations throughout the force rise phase (Fig. 5B). This observation is even more evident in the ΣF_n second derivative profiles (Fig. 5C and D).

Figure 6A, B shows the peak ΣF_n rate and modulations, respectively, averaged across the last 10 trials for the CTS patients and control subjects for each texture condition. Peak ΣF_n rate was significantly higher in CTS patients compared to controls (Figure 6A) as well as during the silk vs. sandpaper conditions, with no significant interaction. To quantify the ΣF_n modulations, the number of zero crossings of the ΣF_n second derivative signals (see Figs. 5C and D) during the force rise phase was determined. The controls produced significantly greater ΣF_n modulations (Figure 6B) than did the CTS patients, confirming the earlier observation. In both groups and for each texture condition, greater than 80% of these ΣF_n modulations occurred during the load phase and none of the *first* zero crossings occurring during the lift. There was neither a significant difference between Textures nor an interaction effect in ΣF_n modulations.

Analysis of peak ΣF_n rate across trials revealed main effects of Texture and Group, with greater peak rate during the silk vs. sandpaper conditions and in the CTS patients vs. controls. There were no differences across Trials or any interactions. Analysis of Trial one alone showed no Texture differences in peak ΣF_n rate, however, there was a Group difference (Fig. 7A). For ΣF_n modulations, there was a main effect of Group (Fig. 7B) when analyzing ΣF_n modulations across trials, with no main effect of Trials, Texture, nor any interactions. Analysis of Trial one revealed a significant Group difference however neither a significant Texture difference nor any interaction was observed.

Digit contact and timing

CTS patients initiated device contact with their index finger first on 51.5% of the trials, whereas, controls showed more or less an equal distribution among digits. Our analysis showed a significant difference between all four distributions (CTS sandpaper, CTS silk, control sandpaper, and control silk; $\chi^2(12) = 41.32$, $P < 0.001$). Post-hoc analysis showed no difference between CTS silk vs. sandpaper or control silk vs. sandpaper. However, there were significant differences in the distributions between Groups, i.e., CTS vs. control silk and CTS vs. control sandpaper ($\chi^2(4) = 21.24$, $P < 0.001$ and $\chi^2(4) = 16.86$, $P < 0.01$, respectively; note that given the Bonferroni corrections for multiple comparisons, differences in the distributions are significant at $P < 0.0125$). CTS patients also spent a longer time between first to last digit contact compared to controls (214 vs. 140 ms, respectively, for sandpaper; 311 vs. 164 ms, respectively, for silk). However, the differences were not statistically significant for Groups, Textures, or Trials. There were also no differences within Group or Texture in preload phase duration (controls: 102 ± 93 ms and 139.0 ± 116 ms for sandpaper and silk, respectively; CTS patients: 114 ± 71 ms and $131 \pm$

84 ms for sandpaper and silk, respectively). Furthermore, no main effect of Trials, Group or Texture was observed for preload duration, nor were there any interactions.

Discussion

The results support our hypotheses, i.e., CTS patients were able to successfully adapt their grip forces relative to texture, but did so inefficiently by producing excessive normal forces compared to controls. Furthermore, CTS patients adapted their forces to texture early in the grasp, i.e., at load onset, and in the first trial when the texture was first introduced. However, two important findings from this study were that CTS patients produced larger peak force rate amplitudes and fewer modulations of normal force during the force rise phase than did the controls. In addition, CTS patients continued to increase their normal forces during the lift phase whereas forces were set at lift onset for the controls. These findings will be discussed in terms of the effect of chronic median nerve compression on the ability to coordinate anticipatory and feedback-driven control for effective and efficient grip force adaptation.

Effective but inefficient force adaptation to texture

CTS patients successfully adapted their normal forces to the changes in object texture as the force exerted during the silk condition was significantly greater than that during the sandpaper condition. This is consistent with previous studies examining the ability of CTS patients to discriminate between textures, identify objects (King, 1997), and adapt grip forces to texture when using two CTS-affected digits (Thonnard et al., 1999). In a whole-hand grasping study, Zhang et al. (2011) observed similar abilities in CTS patients to discriminate between object masses, interpreting this ability as being potentially mediated by proprioceptive information. It is unlikely that the spared muscle, joint, and tendon mechanoreceptors in the forearm and upper arm played any role in the current force adaptations given the nature of the sensory information provided by texture (i.e., tactile) and that the texture differences were observed prior to the application of any load force which is the first grasp event likely to stimulate these mechanoreceptors. Furthermore, the importance of tactile feedback for grip force adaptation to texture has been demonstrated through digital anesthesia which disrupts this force adaptation (Johansson and Westling, 1984). Thus, the successful force adaptation to texture exhibited by the CTS patients suggests these patients have sufficient intact tactile sensory nerve fibers from the CTS-affected digits and/or utilize the non-affected little and ulnar half of the ring finger to discriminate between the different textures presented and integrate this information within the sensorimotor system to effectively modify their grip forces to changes in texture.

However, Zhang et al. (2011) also reported a reduced ability for CTS patients to discriminate between lighter objects despite correctly adjusting forces to heavier objects. This is consistent with a study using fine grades of 100 μm between textures which reported CTS patients' inability to discriminate between the textures (Heywood and Morley, 1992). Thus, it remains to be determined whether (1) CTS patients' effective grip force adaptation to texture becomes ineffective when introduced to more finely graded texture differences, and (2) determining the point at which such a breakdown in grip force adaptation occurs would provide information regarding the extent of injury to the median sensory nerve fibers.

While effectively adapting digit forces to texture, CTS patients did so inefficiently by producing excessive grip forces when compared to healthy controls. It is well established that patients with acute and chronic neurological impairment use excessive grip forces when compared to healthy individuals (Cole et al., 2003; Dun et al., 2007; Hermsdörfer et al., 2003; Iyengar et al., 2009a,b; Jiang et al., 2009; Lowe and Freivalds, 1999; Zhang et al., 2011). Excessive grip force in these individuals may represent an attempt to compensate for

their sensorimotor dysfunction by prioritizing effectiveness, i.e., preventing the object from slipping (Cole et al., 2003; Dun et al., 2007; Hermsdörfer et al., 2003, 2008; Lowe and Frievālds, 1999), over efficiency, i.e., producing just sufficient force for holding the object against gravity. It is likely that the CNS may prioritize effectiveness over efficiency as this could avoid dropping of the object which is commonly reported by patients with severe CTS (Pazzaglia et al., 2010). The trigger in CTS patients for using such a strategy may be the “noisy” tactile information provided by the thumb which bears a significant portion of the object load, thus may be preferentially monitored for object slips by the CNS. For CTS patients the repetitive use of such a strategy could lead to further exacerbation of the median nerve compression and further progression of the syndrome. While the current finding of excessive grip forces in CTS is not novel, to our knowledge this is the first report that increased grip force, similar to the texture differences mentioned above, emerged as early as the load phase. Previous reports have shown excess grip forces at lift and hold onsets (Cole et al. 2003; Zhang et al., 2011), during the lift (Thonnard et al., 1999), and during the hold (Dun et al., 2007). Examining only these later phases of the grasp precludes analysis of the sensorimotor control processes, i.e., anticipatory vs. feedback control, underlying digit force adaptation to object properties, especially texture which can be sensed on digit contact (see below). Moreover, *both* CTS patients and controls produced larger grip forces at load onset in the *first* trial and both groups significantly reduced their grip force in the subsequent trials (Fig. 4). This may indicate that the excessive grip force strategy used by CTS patients may be inherent in healthy individuals as well when faced with manipulating objects with unknown physical properties (Gordon et al., 1993).

Anticipatory vs. feedback force control

The CTS patients appeared to use anticipatory force control after the first few interactions with the object as indicated by single peaked force rate profiles (Gordon and Ghez, 1987) that were scaled as a function of object texture (Fig. 6). Healthy controls exhibited similar changes in force rates to texture, however they also produced a greater number of force modulations than did the CTS patients regardless of texture. This latter observation suggests that, in addition to utilizing anticipatory control, the healthy controls may have also used online sensory feedback to finely tune their digit forces prior to lift. In fact, the healthy controls set their normal force *prior* to lift onset maintaining the same force amplitude from lift onset to hold.

In contrast, after the first few interactions with the object, CTS patients did not appear to use sensory feedback during the load phase as indicated by the lack of force modulations. It is unclear from this result whether not using this “probing” strategy (Johansson and Westling, 1988a) employed by the healthy controls indicates an inability to do so, or is simply a compensatory strategy chosen by the CTS patients. Regardless, CTS patients appear to relying on anticipatory force control which may have led to the patients unnecessarily continuing to increase their normal force amplitude *during* lift. They did so despite the fact that they were already exerting excessive grip forces at lift onset. There are several possible interpretations for this. First, it is possible that CTS patients’ used a compensatory strategy that included pre-programming grip forces not only for the force rise phase, but rather for the force rise *and* the lift phases. However, this does not appear to be the case as all the first force modulations occurred either in the load or preload phases. Second, it is possible that this increase in force during lift represents an inability to sense, in a timely fashion, the termination of the load phase through initiation of object lift (Johansson and Flanagan, 2009). If so, it may point to (1) a difference in the deficits between fast adapting I and II tactile mechanoreceptors (Meissner and Pacinian corpuscles, respectively) in CTS patients, as these receptors are primarily responsible for sensing texture vs. shear forces across the digit as it happens during lift onset (Johansson and Flanagan, 2009), or (2) preferential

monitoring of the CTS-affected digits (e.g., thumb) in detecting changes in object loading (see above). Third, this increase in force could be an attempt to further stabilize the device during the lifting movement that is triggered by proprioceptive information provided by the intact muscle, joint, and tendon mechanoreceptors in the forearm and upper arm as opposed to the slower tactile information provided by the impaired median nerve. Further investigation is needed to tease apart these latter two hypotheses.

In the first trial, when the new object texture is first introduced, healthy individuals have been shown to sense texture differences during the preload phase and modify their digit forces early in the load phase (Cole et al., 1999; Johansson and Westling, 1984; Reilmann et al., 2001). The CTS patients in the current study showed similar abilities as force differences to texture emerged at load onset in the first trial suggesting that the texture changes were appropriately sensed prior to the load phase. Johansson and Westling (1984) observed that healthy individuals took an average of 50 ms between first and second digit contact in a two-digit grasping task and an additional 100 ms for force adaptation to texture to emerge, suggesting that it takes approximately 150 ms to sense the texture, process the information and modify the digit forces accordingly. However, subjects in the current five-digit study had more digit contact time prior to load onset, given the increased number of digits involved. In the current study, healthy controls and CTS patients took on average 152 and 237 ms, respectively, between the times the first and last digit made contact with the object on the first trial. This, in addition to an average of approximately 167 ms for the preload phase provided ample time for the texture to be sensed and that information processed, *even with a slowing in sensory conduction*, to allow for force adaptation to develop by load onset. This assumes that the sensory information provided by a single digit in our multi-digit grasping task is sufficient for appropriate multi-digit force programming. If this is the case, one might expect CTS patients to take advantage of the ability to use all five digits in the current study to initiate contact with the object with their CTS-unaffected, i.e., the little finger. Contrary to this expectation, CTS patients consistently made initial contact with the object using their index finger while healthy individuals showed no preference for initial digit contact.

Limitations

In the current study, only a few CTS patients showed abnormal touch-pressure sensitivity as measured through Semmes-Weinstein monofilaments. However, the main question of this study goes beyond understanding the ability of individuals with CTS to simply discriminate between textures to addressing how well these individuals are able to use this information for efficient and effective object manipulation. Normal touch-pressure sensitivity may indicate normal spatial resolution (Phillips and Johnson, 1981), but to effectively use tactile information for grasping, the timing and pattern of activity across tactile afferents is critical (for review see Johansson and Flanagan, 2009). It may be the temporal aspects of the tactile information that is reflected in the aforementioned behavioral consequences observed in CTS patients. Note that our control subjects did not undergo electrodiagnostic tests, thus there is the possibility of asymptomatic conduction slowing of the median nerve in these individuals. However, we did not observe any outliers in our control population, and if some of our control participants had asymptomatic conduction slowing, our results become even more robust as presumably these control participants would behave similar to CTS patients.

A second limitation of the study is in its reduced statistical power due to the smaller number of subjects after removal of the older participants. It is well established that healthy older individuals (age > 50) have different grasping patterns characterized by higher normal force production compared to their younger counterparts (Cole et al., 1999). However, the force increase in individuals up to the age of 60 has been attributed to increases in skin slipperiness whereas those over the age of 60 experience force increases due to changes in

both skin slipperiness and tactile sensory function. Anticipating that any increase in skin slipperiness would occur in both CTS patients and their age-matched controls, we recruited subjects 60 years old and younger. However, our results suggested differences in the relations between the CTS patients and their controls with respect to age, with those greater than 58 showing opposite results from the younger individuals. As studying the effects of aging on CTS was not the intent of this study, older individuals were excluded from the analysis. However, these results suggest the need for future research addressing the effects of aging on the sensorimotor functions in patients with CTS.

Conclusion

Individuals with CTS were able to modulate grip force relative to texture. However, several specific characteristics distinguish their sensorimotor control from that of healthy individuals, i.e., CTS patients (1) produced larger peak force rate amplitude, (2) produced fewer modulations of normal force and (3) modified forces during the lift phase whereas forces were set at lift onset for the controls. Despite the ability to modify grip forces to changes in textures, the aforementioned characteristics in force adaptation indicate impaired sensorimotor control in CTS patients leading to the production of excessive grip forces which has the potential to exacerbate the median nerve compression. Future work will address the question of how CTS severity influences force coordination and their ability to adapt to object properties.

Acknowledgments

We thank Drs. Chris White and Gary Klein for their aid in interpretation of the electrodiagnostic tests and patient recruiting, respectively. We also thank the electromyography technologists at the Foothills and Rockyview Hospitals in Calgary for their patient recruiting assistance. This publication was made possible by grant number 1R01 HD057152 from the National Institute of Child and Health Development (NICHD) at the National Institutes of Health (NIH). Its contents are solely the responsibility of the authors and do not necessarily represent the official views of NICHD or NIH.

References

- Afifi M, Santello M, Johnston J. Multi-digit force adaptation to texture in patients with carpal tunnel syndrome. *Soc Neurosci.* 2011:Abstr. 897.17.
- Aoki T, Latash ML, Zatsiorsky VM. Adjustments to local friction in multifinger prehension. *J Mot Behav.* 2007; 39:276–90. [PubMed: 17664170]
- Cole KJ, Rotella DL, Harper JG. Mechanisms for age-related changes of fingertip forces during precision gripping and lifting in adults. *J Neurosci.* 1999; 19:3238–47. [PubMed: 10191336]
- Cole KJ, Steyers CM, Graybill EK. The effects of graded compression of the median nerve in the carpal canal on grip force. *Exp Brain Res.* 2003; 148:150–7. [PubMed: 12520402]
- D'Arcy CA, McGee S. Clinical diagnosis of carpal tunnel syndrome. *JAMA.* 2000; 284:1924–5. [PubMed: 11035885]
- De Krom MC, Knipschild PG, Kester AD, Spaans F. Efficacy of provocative tests for diagnosis of carpal tunnel syndrome. *Lancet.* 1990; 335:393–5. [PubMed: 1968125]
- Dun S, Kaufmann RA, Li ZM. Lower median nerve block impairs precision grip. *J Electromyogr Kinesiol.* 2007; 17:348–54. [PubMed: 16616519]
- Forssberg H, Eliasson AC, Kinoshita H, Johansson RS, Westling G. Development of human precision grip. I: Basic coordination of force. *Exp Brain Res.* 1991; 85:451–7. [PubMed: 1893993]
- Franzblau A, Werner RA, Johnston E, Torrey S. Evaluation of current perception threshold testing as a screening procedure for carpal tunnel syndrome among industrial workers. *JOM.* 1994; 36:1015–21. [PubMed: 7823213]
- Gordon AM, Charles J, Steenbergen B. Fingertip force planning during grasp is disrupted by impaired sensorimotor integration in children with hemiplegic cerebral palsy. *Pediatr Res.* 2006; 60:587–91. [PubMed: 16988186]

- Gordon AM, Ingvarsson PE, Forssberg H. Anticipatory control of manipulative forces in Parkinson's disease. *Exp Neurol*. 1997; 145:477–88. [PubMed: 9217084]
- Gordon AM, Quinn L, Reilmann R, Marder K. Coordination of prehensile forces during precision grip in Huntington's disease. *Exp Neurol*. 2000; 163:136–48. [PubMed: 10785452]
- Gordon AM, Westling G, Cole KJ, Johansson RS. Memory representations underlying motor commands used during manipulation of common and novel objects. *J Neurophysiol*. 1993; 69:1789–96. [PubMed: 8350123]
- Gordon J, Ghez C. Trajectory control in targeted force impulses. II. Pulse height control. *Exp Brain Res*. 1987; 67:241–52. [PubMed: 3622687]
- Hermisdörfer J, Elias Z, Cole JD, Quaney BM, Nowak DA. Preserved and impaired aspects of feed-forward grip force control after chronic somatosensory deafferentation. *Neurorehabil Neural Repair*. 2008; 22:374–84. [PubMed: 18223241]
- Hermisdörfer J, Hagl E, Nowak DA, Marquardt C. Grip force control during object manipulation in cerebral stroke. *Clin Neurophysiol*. 2003; 114:915–29. [PubMed: 12738439]
- Heywood JT, Morley JW. Texture discrimination in carpal tunnel syndrome. *Brain*. 1992; 115:1081–92. [PubMed: 1393504]
- Hilburn JW. General principles and use of electrodiagnostic studies in carpal and cubital tunnel syndromes. *Hand Clin*. 1996; 12:205–21. [PubMed: 8724574]
- Iyengar V, Santos MJ, Ko M, Aruin AS. Effect of contralateral finger touch on grip force control in individuals with multiple sclerosis. *Clin Neurophysiol*. 2009a; 120:626–31. [PubMed: 19243992]
- Iyengar V, Santos MJ, Ko M, Aruin AS. Grip force control in individuals with multiple sclerosis. *Neurorehabil Neural Repair*. 2009b; 23:855–61. [PubMed: 19531607]
- Jablecki CK, Andary MT, Floeter MK, Miller RG, Quartly CA, Vennix MJ, et al. American Association of Electrodiagnostic Medicine; American Academy of Neurology; American Academy of Physical Medicine and Rehabilitation. Practice parameter: Electrodiagnostic studies in carpal tunnel syndrome. Report of the American Association of Electrodiagnostic Medicine, American Academy of Neurology, and the American Academy of Physical Medicine and Rehabilitation. *Neurology*. 2002; 58:1589–92. [PubMed: 12058083]
- Jablecki CK, Andary MT, So YT, Wilkins DE, Williams FH. Literature review of the usefulness of nerve conduction studies and electromyography for the evaluation of patients with carpal tunnel syndrome. AAEM Quality Assurance Committee. *Muscle Nerve*. 1993; 16:1392–414. [PubMed: 8232399]
- Jiang L, Cutkosky MR, Ruutinen J, Raisamo R. Using Haptic Feedback to Improve Grasp Force Control in Multiple Sclerosis Patients. *IEEE T ROBOT*. 2009; 25:593–601.
- Johansson, RS. Somatosensory signals and sensorimotor transformations in reactive control of grasp. In: Franzen, O.; Johansson, R.; Terenius, L., editors. *Somesthesia and the Neurobiology of the Somatosensory Cortex*. Basel: Birkhauser Verlag; 1996. p. 271-82.
- Johansson, RS. Sensory input and control of grip. Sensory guidance of movement; Novartis Foundation Symposium; Wiley: Chichester; 1998. p. 45-63.
- Johansson RS, Cole KJ. Sensory-motor coordination during grasping and manipulative actions. *Curr Opin Neurobiol*. 1992; 2:815–23. [PubMed: 1477545]
- Johansson RS, Flanagan JR. Coding and use of tactile signals from the fingertips in object manipulation tasks. *Nat Rev Neurosci*. 2009; 10:345–59. [PubMed: 19352402]
- Johansson RS, Westling G. Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Exp Brain Res*. 1984; 56:550–64. [PubMed: 6499981]
- Johansson RS, Westling G. Signals in tactile afferents from the fingers eliciting adaptive motor responses during precision grip. *Exp Brain Res*. 1987; 66:141–54. [PubMed: 3582528]
- Johansson RS, Westling G. Coordinated isometric muscle commands adequately and erroneously programmed for the weight during lifting task with precision grip. *Exp Brain Res*. 1988a; 71:59–71. [PubMed: 3416958]
- Johansson RS, Westling G. Programmed and triggered reactions to rapid load changes during precision. *Exp Brain Res*. 1988b; 71:72–86. [PubMed: 3416959]

- Johnston, JA.; Santello, M. Multi-digit grasping and manipulation: effect of Carpal Tunnel Syndrome on force coordination. In: Nowak, DA.; Hermsdorfer, J., editors. *Sensorimotor Control of Grasping: Physiology and Pathophysiology*. Cambridge: Cambridge University Press; 2009. p. 285-95.
- Kimura, J. *Electrodiagnosis in Diseases of Nerve and Muscle: Principles and Practice*. 3. New York: Oxford University Press; 2001.
- King PM. Sensory function assessment: A pilot comparison study of touch pressure threshold with texture and tactile discrimination. *J Hand Ther*. 1997; 10:24–8. [PubMed: 9116804]
- Lowe BD, Freivalds A. Effect of carpal tunnel syndrome on grip force coordination in hand tools. *Ergonomics*. 1999; 42:550–64. [PubMed: 10204420]
- Oh, SJ. *Clinical Electromyography: Nerve Conduction Studies*. 3. Philadelphia: Lippincott, Williams & Wilkins; 2003.
- Pazzaglia C, Caliendo P, Granata G, Tonali P, Padua L. "Dropping objects": a potential index of severe carpal tunnel syndrome. *Neurol Sci*. 2010; 31:437–9. [PubMed: 20217442]
- Raghavan P, Krakauer JW, Gordon AM. Impaired anticipatory control of fingertip forces in patients with a pure motor or sensorimotor lacunar syndrome. *Brain*. 2006; 129:1415–25. [PubMed: 16597653]
- Rao AK, Gordon AM, Marder KS. Coordination of fingertip forces during precision grip in premanifest Huntington's disease. *Movement Disord*. 2011; 26:862–9. [PubMed: 21394785]
- Rearick MP, Casares A, Santello M. Task-dependent modulation of multi-digit force coordination patterns. *J Neurophysiol*. 2003; 89:1317–26. [PubMed: 12626614]
- Rearick MP, Santello M. Force synergies for multifingered grasping. Effect of predictability in object center of mass and handedness. *Exp Brain Res*. 2002; 44:38–49. [PubMed: 11976758]
- Reilmann R, Gordon AM, Henningsen H. Initiation and development of fingertip forces during whole-hand grasping. *Exp Brain Res*. 2001; 140:443–52. [PubMed: 11685397]
- Salimi I, Frazier W, Reilmann R, Gordon AM. Selective use of visual information signaling objects' center of mass for anticipatory control of manipulative fingertip forces. *Exp Brain Res*. 2003; 150:9–18. [PubMed: 12698211]
- Santello M, Muratori L, Gordon AM. Control of multidigit grasping in Parkinson's disease: effect of object property predictability. *Exp Neurol*. 2004; 187:517–28. [PubMed: 15144878]
- Thonnard J, Saels P, Van den Bergh P, Lejeune T. Effects of chronic median nerve compression at the wrist on sensation and manual skills. *Exp Brain Res*. 1999; 128:61–4. [PubMed: 10473740]
- Werner RA, Franzblau A, Johnston E. Quantitative vibrometry and electrophysiological assessment in screening for carpal tunnel syndrome among industrial workers: a comparison. *Arch Phys Med Rehabil*. 1994; 75:1228–32. [PubMed: 7979934]
- Werner RA, Franzblau A, Johnston E. Comparison of multiple frequency vibrometry testing and sensory nerve conduction measures in screening for carpal tunnel syndrome in an industrial setting. *Am J Phys Med Rehabil*. 1995; 74:101–6. [PubMed: 7710722]
- Westling G, Johansson RS. Factors influencing the force control during precision grip. *Exp Brain Res*. 1984; 53:277–84. [PubMed: 6705863]
- Winstein CJ, Abbs JH, Petashnick D. Influences of object weight and instruction on grip force adjustments. *Exp Brain Res*. 1991; 87:465–9. [PubMed: 1769397]
- You H, Simmons Z, Freivalds A, Kothari MJ, Naidu SH. Relationships between clinical symptom severity scales and nerve conduction measures in carpal tunnel syndrome. *Muscle Nerve*. 1999; 22:497–501. [PubMed: 10204785]
- Zhang W, Johnston JA, Ross MA, Smith AA, Coakley BJ, Gleason EA, et al. Effects of Carpal Tunnel Syndrome on adaptation of multi-digit forces to object weight for whole-hand manipulation. *PLoS ONE*. 2011; 6:1–13.

Highlights

1. We examine grip force adaptation in carpal tunnel syndrome (CTS) to understand how the Central Nervous System integrates sensory information from CTS-affected and non-affected digits with motor commands to fine-tune multi-digit forces to changes in object texture.
2. We found CTS patients were able to adapt their digit forces to texture but did so using excessive force which could lead to an exacerbation of the median nerve compression.
3. Such digit forces were produced through an imbalance between anticipatory and feedback control mechanisms.

Figure 1. Grip manipulandum. Note that normal and tangential (vertical) forces are those perpendicular and parallel to the grip surface, respectively.

Figure 2.

Grip phase determination. A) Normal forces for each digit as a function of time for a single trial. The different grasp phases, force rise, lift, and hold are delineated by a, b, and c, respectively. B) The sum over all five digits of the tangential forces as a function of time. C) Tangential force rate as a function of time.

Figure 3. Normal forces. Sum of the digit normal forces (ΣF_n) at load, lift, and hold onset, as well as mean hold for A) all, B) young, and C) older participants.

Figure 4. Normal force trial data. Sum of the digit normal forces (ΣF_n) at load onset across trials.

Figure 5.

Normal force derivatives. A) and B) show the 1st derivative of the sum normal force (ΣF_n) during the force rise phase across all 12 trials for one CTS patient (no 1) and her control, respectively, during the sandpaper condition. C) and D) show the 2nd derivative for the same 2 participants. Note: The y-axes are different for each panel and the data have been time-normalized for display purposes only.

Figure 6. Average force data. A) Peak ΣF_n rates and B) ΣF_n modulations produced in the force rise phase by CTS patients and control subjects during both texture conditions. * $P < 0.05$, ** $P < 0.01$

Figure 7. First trial force data. A) peak ΣF_n rates and B) ΣF_n modulations produced on the first trial by CTS patients and control subjects during both texture conditions. * $P < 0.05$, ** $P < 0.01$

Table 1

Patient characteristics and electrodiagnostic results for the median nerve

CTS Patients											Control
No	Age	Gender	Dominant Hand	Tested Hand	Study	Digit	Electrodiagnostic tests (abnormal values in bold) ¹				Age
							Onset Latency (ms)	Peak Latency (ms)	Amplitude ²	Velocity (m/s)	
1	33	F	R	L	Sensory	Index	4.3	5.4	8.3	33	33
					Ring	NR	NR	NR	NR		
					Motor	5		5.8			
2	53	F	R	R	Sensory	Index	3.9	5	13.1	36	55
					Ring	4.3	5.8	7.3	33		
					Motor	5.2		6.3			
3	57	M	Both	L	Sensory	Index	3.7	4.8	12	37.8	55
					Ring	4.5	5.5	5.7	31.1		
					Motor	5		10.8			
4	43	M	R	R	Sensory	Index	3.2	3.9	35.5	44	45
					Ring	3.6	4.4	19.1	39		
					Motor	4.7		10.9			
5	42	F	L	R	Sensory	Index	4.3	5.5	10.9	33	44
					Ring	5.8	7	4.4	24		
					Motor	6.8		8.7			
6	40	F	R	R	Sensory	Index	3.2	3.8	28.2	44	41
					Ring	3.3	4.1	11.7	42		
					Motor	3.7		11.1			
7**	48	F	R	R	Sensory	Index	2.9	3.6	28.8	48	48
					Ring	2.4	2.9	15.8	58		
					Motor	3.8		14.7			
8	47	F	R	R	Sensory	Index	4.3	4.8	16	39	46
					Ring	5.3	5.8	6.9	35		
					Motor	6.4		11.9			

CTS Patients										Control	
No	Age	Gender	Dominant Hand	Tested Hand	Study	Digit	Electrodiagnostic tests (abnormal values in bold) ¹				Age
							Onset Latency (ms)	Peak Latency (ms)	Amplitude ²	Velocity (m/s)	
9 *	59	F	L	R	Sensory	Index	3.8	4.7	10.2	37	60
						Ring	4.2	5.5	2.1	33	
					Motor		4.5		7.1		
10 *	59	F	R	R	Sensory	Index	3.3	4.1	16	42	59
						Ring	3.6	4.3	8	39	
					Motor		5.2		9		
11 *	59	F	R	R	Sensory	Index	3.3	4	21	42	60
						Ring	3.4	4.3	14.1	41	
					Motor		4.1		10.9		

NR no response

^{*} CTS patients placed in the older group

^{**} Confirmed CTS as this patient has delayed palmar ortho sensory onset and peak latency (2.1 & 2.8 ms, respectively) compared to normative values (2 & 2.5 ms, respectively)

¹ Normative values are listed in Table 2.

² Onset to peak amplitude values for sensory and motor studies are in microvolts and millivolts, respectively.

Table 2

Normative values for electrodiagnostic tests

Study	Digit	Age	Gender	Onset Latency (ms)	Peak Latency (ms)	Amplitude ^I	Velocity (m/s)
Sensory	Index	19-49	Both	3.3	4.1	15	42
		50-79		3.3	4.1	8	42
	Ring	All		2.8	3.3	7.9	50
Motor [*]	NA	19-49	Male		4.6		
			Female		4.3		
		50-79	Male		4.8		
			Female		4.6		
		19-39	Both			4.7	50
		40-59				4.2	45
		60-79				1.8	45

^I Onset to peak amplitude values for sensory and motor studies are in microvolts to millivolts respectively

^{*} Note that for motor studies, different age ranges are used for peak latency compared to amplitude and velocity.

Table 3

Sensory, and provocative test results

No	Semmes-Weinstein monofilament [*]					Provocative tests ^{**}		
	Thumb	Index	Middle	Ring	Little	Phalens	Compression	Tinel
1	1	1	1	1	1	+	+	+
2	2	1	2	1	1	+	-	+
3	1	1	1	1	1	+	-	-
4	1	2	2	1	1	-	-	-
5	1	1	1	1	1	-	+	-
6	1	1	1	1	1	+	+	-
7	2	2	2	1	1	-	+	-
8	1	1	1	1	1	+	+	-
9	1	1	1	1	1	+	+	-
10	1	1	1	1	1	+	+	+
11	1	1	1	1	1	-	-	-

^{*} 1 and 2 signify forces of 0.0677 g and 0.4082 g, respectively

^{**} "+," and "-," indicate patient did and did not, respectively, experience pain, numbness, and/or tingling in the palmar portion of the lateral three and half fingers.

Table 4

All statistical results

Test	Variable	Main Effect	F-value	P-value	Pairwise comparisons
2×2 ANOVAs : Texture X Group	Overall Average ΣF_n	Load onset	F[2,20] = 7.6	$P < 0.05$	Silk > Sandpaper
		Lift onset	F[2,20] = 34.54	$P < 0.001$	Silk > Sandpaper
		Hold onset	F[2,20] = 29.30	$P < 0.001$	Silk > Sandpaper
		Mean hold	F[2,20] = 27.63	$P < 0.001$	Silk > Sandpaper
	Young Average ΣF_n	Load onset	F[2,14] = 7.61	$P < 0.05$	Silk > Sandpaper
		Lift onset	F[2,14] = 38.50	$P < 0.001$	Silk > Sandpaper
		Hold onset	F[2,14] = 6.25	$P < 0.05$	CTS > Control
		Mean hold	F[2,14] = 38.80	$P < 0.001$	Silk > Sandpaper
	Hold ΣF_n - Lift ΣF_n	Group	F[2,14] = 6.87	$P < 0.05$	CTS > Control
		Texture	F[2,14] = 25.24	$P < 0.001$	Silk > Sandpaper
		Group	F[2,14] = 4.86	$P < 0.05$	CTS > Control
		Texture	F[2,14] = 7.09	$P < 0.05$	CTS > Control
	Load duration	Group	F[2,14] = 9.72	$P < 0.05$	Control > CTS
		Texture	F[2,14] = 7.49	$P < 0.05$	CTS > Control
		Group	F[2,14] = 16.7	$P < 0.01$	Silk > Sandpaper
		Texture	F[2,14] = 5.14	$P < 0.05$	Control > CTS
	ΣF_n rate pulse duration	Group	F[2,14] = 7.98	$P < 0.05$	Control > CTS
		Texture	F[2,14] = 7.61	$P < 0.05$	Silk > Sandpaper
		Group	F[2,14] = 9.13	$P < 0.01$	CTS > Control
		Texture	F[2,14] = 9.03	$P < 0.01$	Silk > Sandpaper
	T1 ΣF_n modulations	Group	F[2,14] = 7.76	$P < 0.05$	Control > CTS
		Texture	F[2,14] = 7.42	$P < 0.01$	T1 > Average
		Group	F[2,14] = 23.62	$P < 0.001$	Silk > Sandpaper
		Texture	F[2,14] = 5.77	$P < 0.01$	T1 > Average
$2 \times 2 \times 3$ ANOVAs: Texture X Group X Trial	Young Average ΣF_n	Texture	F[2,14] = 58.14	$P < 0.001$	Silk > Sandpaper
		Trials	F[4,28] = 7.36	$P < 0.01$	T1, T2 > Average
		Texture	F[2,14] = 58.14	$P < 0.001$	Silk > Sandpaper
		Trials	F[4,28] = 7.36	$P < 0.01$	T1, T2 > Average

Test	Variable	Main Effect	F-value	P-value	Pairwise comparisons
		Texture	$F[2,14] = 62.49$	$P < 0.001$	Silk > Sandpaper
		Texture	$F[2,14] = 42.02$	$P < 0.001$	Silk > Sandpaper
	Mean hold	Texture	$F[2,14] = 8.72$	$P < 0.05$	Silk > Sandpaper
		Group	$F[2,14] = 7.55$	$P < 0.05$	CTS > Controls
	Peak Σ F _n rate	Trial	$F[4,28] = 11.29$	$P < 0.001$	T1 > T2, Average
		Texture	$F[2,28] = 10.13$	$P < 0.05$	Sandpaper > Silk
	Σ F _n rate pulse duration	Group	$F[2,28] = 5.85$	$P < 0.05$	Controls > CTS
		Group	$F[2,14] = 7.55$	$P < 0.05$	Controls > CTS
	ΣF_n modulations				