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Carpal tunnel syndrome impairs sustained precision pinch performance

Ke Li, Peter J. Evans, William H. Seitz Jr., and Zong-Ming Li*

Hand Research Laboratory, Departments of Biomedical Engineering, Orthopaedic Surgery, and Physical Medicine and Rehabilitation, Cleveland Clinic, Cleveland, OH, USA

Ke Li: ke.li.phd@gmail.com; Peter J. Evans: evansp2@ccf.org; William H. Seitz: seitzw@ccf.org; Zong-Ming Li: liz4@ccf.org

Abstract

Objective—The purpose of this study was to investigate effects of carpal tunnel syndrome (CTS) on digit force control during a sustained precision pinch.

Methods—Eleven CTS individuals and 11 age- and gender-matched healthy volunteers participated in the study. The subjects were instructed to isometrically pinch an instrumented apparatus for 60 s with a stable force output. Visual feedback of force output was provided for the first 30 s but removed for the remaining 30 s. Pinch forces were examined for accuracy, variability, and inter-digit correlation.

Results—CTS led to a decrease in force accuracy and an increase in amount of force variability, particularly without visual feedback ($p < 0.001$). However, CTS did not affect the structure of force variability or force correlation between digits ($p > 0.05$). The force of the thumb was less accurate and more variable than that of the index finger for both the CTS and healthy groups ($p < 0.001$).

Conclusions—Sensorimotor deficits associated with CTS lead to inaccurate and unstable digit forces during sustained precision pinch.

Significance—This study shed light on basic and pathophysiological mechanisms of fine motor control and aids in development of new strategies for diagnosis and evaluation of CTS.

Keywords

Carpal tunnel syndrome; Precision pinch; Force accuracy; Force variability; Force coordination

1. Introduction

Carpal tunnel syndrome (CTS) is the most common peripheral entrapment neuropathy caused by chronic compression of the median nerve. The median nerve innervates some intrinsic muscles in the hand and relays sensory information from the palmar aspect of the thumb, the index and middle fingers, and the lateral half of the ring finger. Prolonged

compression on the nerve in the carpal tunnel leads to sensory symptoms such as paresthesia (tingling, burning and itching), numbness and pain, as well as motor symptoms such as stiffness, clumsiness and weakness of the hands (Rosenbaum and Ochoa, 2002). These sensory and motor deficits impair hand functions for manual activities of daily living such as buttoning of clothes, holding a book while reading, and gripping of a telephone handset (Levine et al., 1993), which require well controlled digit forces. Understanding of the effects of CTS on digit force control extends and complements the existing clinical tools to diagnose and evaluate CTS (Arendt-Nielsen et al., 2004).

Previous studies on digit force control due to peripheral median neuropathy have resulted in inconsistent findings. In two-digit precision grip performed with the thumb and index finger, CTS patients exerted greater grip force than healthy subjects when holding a tool (Lowe and Freivalds, 1999). Increased grip force magnitudes were also observed in several simulated peripheral neuropathy studies via mechanical compression of the median nerve at the wrist (Cole et al., 2003), anesthetic injection to the carpal tunnel to block the median nerve (Dun et al., 2007), and local anesthesia of the digital nerves (Augurelle et al., 2003). In contrast, conflicting findings were also reported that both CTS individuals and the healthy controls had similar grip force and grip-to-load force ratio with whole hand gripping (Nowak et al., 2003), generated similar extent of compensatory moment for a full hand grasping (Zhang et al., 2012), and equivalently modulated the grip force in relation to friction during two-digit gripping (Thonnard et al., 1999). The effects of CTS on grasping function can be influenced by a number of factors such as task specifications (e.g. vertical lifting, horizontal moving or static holding), number of digits engaged in grasping, nerve impairment conditions, and available sensory modalities (e.g. grasping under visual (Zhang et al., 2012) or non-visual guidance (Dun et al., 2007)).

Among many manual functions, precision pinch using the thumb and index finger is a common daily manual task, and an effective, reliable, and easy to perform testing paradigm. During a precision pinch, the thumb and index finger intricately coordinate with each other to apply proper amount of force (Gordon et al., 1991; Li and Li, 2013; Marquardt and Li, 2013; Nowak and Hermsdorfer, 2002; Westling and Johansson, 1984). Because CTS prominently impairs the sensory and motor function of the thumb and index finger, the seemingly effortless task of precision pinch for an intact hand may pose challenges to patients with CTS. For example, a CTS patient may show difficulty in coordinating the thumb and index finger for precision pinch forces and movements. Pathomechanics during precision pinch could reveal underlying sensorimotor deficit associated with CTS.

Applying digit force during precision pinch involves a complex sensorimotor process. The somatosensory system, including the tactile sensation and proprioception, plays a crucial role in digit force control (Nowak and Hermsdorfer, 2005; Rothwell et al., 1982). Visual cues supply information about the object's property for anticipatory force control (Jenmalm, 1997). During prolonged isometric contraction, visual feedback of force production in comparison with target force improves the force accuracy and stability (Baweja et al., 2009; Jordan and Newell, 2004), and modulates inter-digit force coordination (Li et al., 2013a). The uncertainty of one sensory modality results in increased dependency on other afferent information (Calvert et al., 2004), and individuals with CTS who have impaired hand

sensorimotor function could increasingly rely on visual feedback to maximize task performance. However, the extent to which CTS affects digit force control with and without visual feedback remains to be understood.

The current study aimed to examine the effects of CTS on force accuracy, variability, and inter-digit force coordination during sustained precision pinch with and without visual feedback. We hypothesized that CTS subjects, compared to the healthy controls, would perform precision pinch with lower force accuracy, higher force variability and reduced inter-digit force coordination, particularly under the condition without visual feedback.

2. Methods

2.1. Subjects

Eleven CTS patients and 11 age- and gender-matched healthy volunteers participated in this study. All participants gave their written informed consent according to the protocols approved by the Institutional Review Board. The subject characteristics are shown in Table 1.

Inclusion criteria for both CTS and healthy subjects were: (1) age 21–70 years old, (2) right-hand dominance verified by Edinburgh Handedness Inventory (Oldfield, 1971), and (3) normal or correct-to-normal vision. The CTS subjects received a clinical diagnosis of CTS in the right hand (Keith et al., 2009) which was supported by satisfying at least three of the following criteria: (a) history of paresthesias, pain, and/or numbness in the median innervated hand territory persisting for at least 3 months; (b) positive provocative maneuvers (Tinel's sign, Phalen's test, and/or median nerve compression test); (c) abnormal electrodiagnostic testing consistent with median nerve neuropathy at/or distal to the wrist (sensory latency > 3.7 ms and/or motor latency > 4.6 ms) (Stevens et al., 1999); and (d) an overall CTS Severity Questionnaire score of greater than 1.5 (Levine et al., 1993). For the control group, the inclusion criteria were (1) gender- and age-matched to a CTS subject within ± 5 years and (2) no history of disease, injury, or previous complications involving the hand and upper extremity. The exclusion criteria for CTS and control subjects included: (1) ulnar, radial, or proximal median neuropathy; (2) existence of a central nervous system disease (e.g., multiple sclerosis, myasthenia gravis, Parkinson's disease); (3) pregnancy; (4) history of trauma or surgical intervention to the hand/wrist; (5) rheumatoid arthritis or osteoarthritis of the hand/wrist; and (6) diabetes.

The following tests were performed before the pinch tests: (1) anthropometric data including the size of the right hand; (2) maximal voluntary contraction forces by pinch with the thumb and index finger and the full hand grip; (3) tactile sensation test using Semmes Weinstein Monofilament for the five digits; (4) Michigan hand outcomes questionnaire (Chung et al., 1999); and (5) Levine's severity questionnaire (Levine et al., 1993). The tactile sensation test and maximal voluntary contraction test were only performed on the right hands.

2.2. Experimental set-up

The experimental set-up for the sustained pinching task has been described in a previous study (Li et al., 2013a). Briefly, a pinch apparatus was designed to measure fingertip forces

at the digit-object interfaces using two transducers (Nano17, ATI Industrial Automation, Inc., Apex, NC). The pinch apparatus was rigidly fixed to a testing table at a distance of 35 cm in front of the subject (Fig. 1A). The pinching surfaces were covered with 100 grit sandpaper and were oriented in parallel with a pinch span of 2 cm (Fig. 1B). A 22-in. computer monitor, with a viewing area of 1024×1280 pixels, was positioned 50 cm in front of the subject. Graphically displayed in the center of the screen was a tank with overall dimensions of 200 (width) $\times$ 500 (height) pixels. Along the vertical direction of the tank, a scale of 0–10 N was provided. A bar in the tank fluctuated in real-time indicating the average normal force exerted onto the pinch apparatus by the thumb and index finger. A target line (1 pixel in width) at 5 N was also displayed in the tank. For the non-visual feedback condition, the target line and bar depicting the real time force were not displayed. The visual feedback conditions and data collection were implemented using a custom LabVIEW (National Instrument, Austin, TX) program. Force signals were recorded at a sampling frequency of 1000 Hz.

2.3. Test procedures

Each subject sat comfortably in a height adjustable chair at the testing table. The right upper arm was approximately abducted 60° in the frontal plane and flexed 30° in the sagittal plane. The elbow was flexed approximately 120° and the forearm rested on a support and in a neutral pronation/supination position. Then, subjects were instructed to pinch the apparatus with the pulps of their thumb and index finger for 60 s. During the first 30 s, the computer monitor displayed the target line and real-time force bar. Subjects were instructed to steadily maintain their pinch force, which was the average force of thumb and index finger, to match as closely as possible the target line at 5 N. After 30 s, the visual information of the target force and real-time force bar were removed and the subjects were instructed to maintain their prior force level as accurately and stably as possible for the remaining 30 s. Each subject performed six trials with a 2-min rest between trials to minimize muscle fatigue.

2.4. Data analysis

The force was applied under two sensory conditions: with visual feedback (0–30 s) and without visual feedback (30–60 s). For each condition, data in the first 10 s was excluded, thereby leaving the 10–30 s (under the visual condition) and 40–60 s (under the non-visual condition) for subsequent data analyses.

Force accuracy was quantified using root mean square error (RMSE) between the actual force ($x(i)$) and the force target (x_{tar}) (Baweja et al., 2009). The RMSE was calculated as:

$$RMSE = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x(i) - x_{tar})^2}, \quad (1)$$

where n is the numbers of force samples.

The amount of force variability was quantified as coefficient of variation (CV) of the force signals. The CV was calculated as the ratio of standard deviation to the mean force (MF).

The structural force variability was examined using detrended fluctuation analysis (DFA). According to the DFA algorithm, each force signal, $x(i)$, was first integrated as follows:

$$f_{\text{DFA}}(k) = \sum_{i=1}^k (x(i) - MF), \quad (2)$$

Then, the integrated force signal was divided into windows of equal length m ($m = 10-1000$). In each window, the local trend was estimated using a linear least-squares fit, $\tilde{f}_{\text{DFA}}(k)$. The root mean square, $F_{\text{DFA}}(m)$, was calculated over the window of length m .

$$F_{\text{DFA}}(m) = \sqrt{\frac{1}{m} \sum_{k=1}^m [f_{\text{DFA}}(k) - \tilde{f}_{\text{DFA}}(k)]^2} \quad (3)$$

The scaling exponent, α_{DFA} , is the slope of the $\log(n)$ versus $\log F_{\text{DFA}}(n)$ plot and reflects long-range auto-correlation of the time series (refer to Li et al., 2013a for more details).

Detrended cross-correlation analysis (DCCA) was applied to examine the time-dependent structure of the force correlation between the digits (Li et al., 2013a). Using the DCCA algorithm, individual forces were integrated and then the covariance between the integrated data was calculated. This covariance was divided into $N-m$ overlapping windows, where N is the data length of each time series and m is the window size. Within each window, a linear least-squares fit was determined and the covariance of the residuals for each m was calculated as follows:

$$f_{\text{DCCA}}^2(m, i) = \frac{1}{m-1} \sum_{k=i}^{i+m} (R_k - \tilde{R}_{k,j}) (R'_k - \tilde{R}'_{k,j}), \quad (4)$$

where R_k and R'_k are the integrated forces of the thumb and the index finger, respectively, and $\tilde{R}_{k,j}$ and $\tilde{R}'_{k,j}$ are the local trends of R_k and R'_k . The detrended covariance $F_{\text{DCCA}}(n)$ was calculated by averaging the covariance over all windows.

$$F_{\text{DCCA}}(m) = \sqrt{\frac{1}{N-m} \sum_{i=1}^{N-m} f_{\text{DCCA}}^2(n, i)} \quad (5)$$

Scaling exponent, α_{DCCA} , is the slope of $\log(m)$ versus $\log F_{\text{DCCA}}(m)$ plot and is an indication of long-range cross-correlation between the forces exerted by the thumb and index finger.

The parameters of force accuracy (RMSE), amount variability (CV) and structural variability (α_{DFA}) were applied to individual digit forces and the average force of the two digits. Two digit forces were used to calculate α_{DCCA} .

2.5. Statistical analyses

Statistical analyses were performed using SPSS (SPSS Inc., Chicago, IL). Normality of all parameters was verified using the Shapiro–Wilk test. Three-way analyses of variance were performed on the force outcomes (MF, RMSE, CV, α_{DFA}) with a between-subject group factor (CTS versus Control) and repeated measures factors of feedback (with versus without visual feedback) and digit (thumb versus index finger). Force correlation (α_{DCCA}) was examined by a two-way analysis of variance with a between-subject group factor (CTS versus Control) and a repeated measure feedback factor (with and without visual feedback). A p -value less than 0.05 was considered statistically significant.

3. Results

Forces exerted by the thumb and index finger from a representative subject are shown in Fig. 2. No significant differences were observed in pinch force levels between CTS and control groups with and without visual feedbacks (Fig. 3A, $p = 0.072$). But feedback conditions and digit factors significantly affected the force outputs (Fig. 3A and B, $p < 0.001$). Removal of visual feedback led to a decreased pinch force for both CTS patients and controls (Fig. 3A, $p < 0.001$). The thumb exerted lower force than the index finger (Fig. 3B, $p < 0.001$). With visual feedback, pinch forces were 4.86 ± 0.20 N for the CTS group and 4.82 ± 0.15 N for the control group. Without visual feedback, pinch force for the CTS and control groups were 4.38 ± 0.86 N and 4.65 ± 0.31 N, respectively. There was a significant interaction in force output between the group and feedback factors ($p < 0.001$), but no significant interaction between the digit and group factors ($p = 0.708$) or between the digit and feedback factors ($p = 0.723$).

There were significant main effects of the group, feedback and digit factors on the force accuracy quantified by RMSEs (Fig. 4, $p < 0.001$). Although the CTS and control groups had comparable RMSEs with visual feedback ($p = 0.818$), RMSE in CTS was significantly higher than that in the controls without visual feedback (Fig. 4A, $p < 0.001$). There was significant interaction between the group and feedback factors ($p < 0.001$). No significant interaction was observed between the digit and feedback factors (Fig. 4B, $p = 0.258$) or between the digit and group factors (Fig. 4B, $p = 0.940$).

There were significant main effects of the group, feedback and digit factors on the force variability quantified by CV (Fig. 5, $p < 0.001$). The CTS group had significantly higher CV than the control group for with and without visual feedback conditions (Fig. 5A, $p < 0.001$). The removal of visual feedback significantly increased the CV for both groups, and the thumb had higher CV than the index finger (Fig. 5B, $p < 0.001$). There were significant interactions between the digit and feedback factors and between the group and feedback factors for CV ($p < 0.05$). However, interaction between the digit and group factors was not significant for CV (Fig. 5B, $p = 0.762$).

The scaling exponent (α_{DFA}) to examine the structural variability of pinch force was significantly affected by the feedback factors (Fig. 6A, $p < 0.001$), but no significant difference was observed between the CTS and control groups (Fig. 6A, $p = 0.563$). Under both feedback conditions, the thumb had higher α_{DFA} than the index finger (Fig. 6B, $p <$

0.001). There was a significant interaction between the digit and feedback factors (Fig. 6B, $p < 0.001$).

Visual feedback significantly affected the scaling exponent (α_{DCCA}) of cross-correlation analysis of the thumb and index finger forces (Fig. 7, $p < 0.001$). The α_{DCCA} increased from 1.10 ± 0.11 with visual feedback to 1.36 ± 0.15 without visual feedback for the CTS subjects. Similarly, the α_{DCCA} increased from 1.08 ± 0.14 to 1.33 ± 0.12 after removing the visual feedback for the controls. There was no significant difference in α_{DCCA} between the CTS and control groups (Fig. 7, $p = 0.147$).

4. Discussion

This study investigated the effects of CTS on force application and control during sustained precision pinch with the thumb and index finger. Characteristics of pinch forces were examined for (1) force accuracy; (2) force variability, including the amount and structure of variability; and (3) inter-digit force coordination. Two sensory feedback conditions, including and excluding visual feedback during force production, were studied. The main findings demonstrated: (1) CTS led to a decrease in force accuracy and an increase in amount of force variability, particularly as the force was applied without visual feedback of force production; (2) CTS did not affect either the structure of force variability of individual digits or the correlation of the applied forces between the two digits; and (3) the force of the thumb was less accurate and more variable than that of the index finger for both the CTS and healthy controls. These findings have manifold implications for understanding the mechanisms of digit force control and pathokinetic functions associated with CTS.

4.1. Effects of CTS on the force accuracy

Dexterous manipulation requires accurately mediated digit forces according to sensory feedbacks at the digit-object interface. Individuals with intact sensorimotor function are able to apply proper amount of digit forces with respect to the mechanical properties (e.g. mass, shape, or surface friction) of a grasped object and the task specifications (e.g. lifting and holding). However, those with sensorimotor deficits apply excessive grip force to maintain a larger safety margin than necessary for dexterous manipulation of objects. This non-optimal force control has been observed in individuals after digital anaesthesia (Augurelle et al., 2003; Edin et al., 1992; Johansson and Westling, 1984), external compression at the carpal tunnel (Cole et al., 2003), peripheral median nerve block (Dun et al., 2007), and digit cooling (Nowak and Hermisdorfer, 2003). The current study showed that, in a precision pinch on a fixed object, CTS and control subjects applied similar grip forces with visual feedback of force application. However, when the visual feedback was removed, CTS subjects applied less accurate grip force than the controls, indicating CTS-induced sensorimotor deficits for erroneous force output. The sensorimotor deficits include reduced tactile sensitivity confirmed by the Semmes Weinstein monofilament scores, prolonged sensory and motor latencies, and the diminished sensory and motor action potentials (Table 1). Interestingly, CTS patients are capable of compensating for the sensorimotor deficits with visual feedback of force application with presumably intact visuomotor function to output accurate pinch forces (Nowak et al., 2003; Thonnard et al., 1999; Zhang et al., 2012).

4.2. Effects of CTS on force variability

CTS led to an increase in variability of the pinch forces under both visual and non-visual conditions. This finding suggests that the sensorimotor deficits associated with CTS result in an incapability of maintaining steady digit forces. The reduction of force steadiness in the CTS patients may be attributed to the sensorimotor noise, which is associated with uncertainty in the process of estimating the state of the sensory inputs and controlling the motor system (Kording and Wolpert, 2006). CTS induces sensory deficits in the peripheral receptors (Gritsenko et al., 2007) and afferent pathway (Arendt-Nielsen et al., 2004), muscle weakness (Li et al., 2004), and joint stiffness (Gehrmann et al., 2008); as such, CTS patients are expected to have elevated sensorimotor noises, which contribute to the increased force variability. Furthermore, the sensorimotor noises inherent in CTS cannot be compensated for by visual feedback because increased force variability was observed for CTS patients under both visual and non-visual conditions.

4.3. Effects of CTS on the structure of force variability

Variability in movement quantified by CV reveals the amount of variation on a magnitude basis, but does not provide information regarding how the variability changes over time. Improved understanding of movement or force variability is achieved examining the structure of variability (Jordan and Newell, 2004). DFA analysis demonstrated that without visual feedback the DFA exponent was greater than that with visual feedback for both the CTS and control groups, suggesting that absence of visual feedback reduced the structural variability of pinch forces (Athreya et al., 2012; Li et al., 2013a). This finding corroborates previous studies demonstrating that visual feedback altered the time-dependent properties of force variability during a sustained contraction by a single digit (Athreya et al., 2012; Hong and Newell, 2008; Sosnoff and Newell, 2005) or during pinch with the thumb and index finger (Deutsch and Newell, 2002, 2003; Li et al., 2013a; Vaillancourt et al., 2001). Higher irregularity of pinch force under the visual condition is probably attributed to visual-guided force correction; whereas the central nervous system exerts a less fluctuated muscle contraction in the absence of this visuomotor correction (Athreya et al., 2012; Baweja et al., 2009). The comparable structural variability between the CTS and control groups supports the idea that the central nervous system plays a dominant role in regulating structural variability (Sosnoff and Newell, 2006). CTS, as a peripheral neuropathy, does not seem to influence the structural variability.

4.4. Effects of CTS on inter-digit force coordination

The effects of CTS on the inter-digit force coordination was examined to understand whether (a) the thumb and index finger played the same role in contributing to the error and variability of pinch force, (b) the effects of CTS were digit-specific, and (c) the inter-digit force correlation was influenced by CTS. Although the thumb is more powerful than the index finger for maximal voluntary contraction (Li and Harkness, 2004; Li et al., 2003), we found that for precision pinch the thumb exerted relatively lower normal force than the index finger. The unequal contributions of the thumb and index finger to the total pinch force are probably a result of the built-in anatomical and neural connections that pre-determine synergistic modes for force coordination in human digits (Li et al., 2013b).

Compared to the index finger, the thumb applied forces with lower accuracy, higher amount of variability, and lower structural variability (α_{DFA} of the thumb is higher than that of the index finger). These findings suggest a digit-specific force control for precision pinch, which are associated with the digit's position configuration, musculature, and dynamical degrees of freedom (Li et al., 2013b; Mitra et al., 1998; Newell et al., 2003).

The time-dependent structure of inter-digit force correlation (α_{DCCA}), changed from a pink noise pattern (1.09 and 1.08 for CTS and control subjects, respectively) with visual feedback to a Brown noise pattern (1.36 and 1.33 for CTS and control subjects, respectively). These results suggested a simplified structure of the force correlation after removing visual feedback, which is consistent with previous notions that under merely somatosensory feedback the two digits were more tightly coupled (Deutsch and Newell, 2002; Li et al., 2013a; Morrison and Newell, 1998). CTS did not affect inter-digit force correlation, suggesting that the dynamical degrees of freedom and spatiotemporal coordination of the two digits are based on a higher level control and not affected by the impaired peripheral nerve disorder associated with CTS (Burstedt et al., 1997).

5. Conclusion

This study investigated the effects of CTS on force accuracy, force variability, structure of force variability, and inter-digit force coordination during sustained precision pinch. CTS individuals exerted a less accurate and less stable pinch force than the healthy controls particularly when relying on the somatosensory feedback without the visual feedback of produced forces. This provides evidence that the sensorimotor deficits associated with CTS lead to a deterioration of fine motor control for digit force production. However, CTS did not affect the structural variability of pinch force or inter-digit force correlation, suggesting that higher level mechanisms rather than peripheral nerve dysfunction regulates the dynamic structure of digit force. Compared to the index finger, the thumb applied force with lower accuracy and higher variability, but CTS did not affect the inter-digit force correlation. Visual feedback compensates for the CTS-induced somatosensory deficits for force accuracy, and regulates force structural variability and the inter-digit force coordination. The findings of this study improve the understanding of basic and pathological mechanisms of sensorimotor function for precision pinch force control.

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HIGHLIGHTS

- Sensorimotor deficits associated with carpal tunnel syndrome (CTS) lead to reduced accuracy and stability in digit force control for precision pinch.
- Visual force feedback compensates for force production errors associated with CTS.
- CTS did not affect the structure of force variability or force correlation between digits.

Fig. 1. Experimental setup for the pinch task. (A) A subject interfacing with the pinch apparatus while viewing the monitor for force feedback. (B) Close-up of the pinching posture while the digits are interfacing with the apparatus.

Fig. 2. Forces of the thumb and index finger from representative CTS and healthy subjects. Visual feedback was removed at 30 s. Force target level was at 5 N.

Fig. 3.

Mean force (MF) of the CTS and healthy subjects. (A) MFs of pinch force under visual and non-visual conditions. (B) MFs of the forces of the thumb and index finger under visual and non-visual. *Significant difference between the CTS and control groups ($p < 0.001$). §Significant difference between the thumb and index finger under the same feedback condition ($p < 0.001$). †Significant difference between the visual and non-visual conditions ($p < 0.001$).

Fig. 4.

Root mean square error (RMSE) between the actual force and the force target of the CTS and healthy subjects. (A) RMSEs of pinch force under visual and non-visual condition. (B) RMSEs of the forces exerted by the thumb and index finger under visual and non-visual conditions. The markers have the same meanings as in Fig. 3.

Fig. 5. Coefficient of variation (CV) of the forces applied by the CTS and healthy subjects. (A) CVs of pinch force under visual and non-visual conditions. (B) CVs of the forces exerted by the thumb and index finger under visual and non-visual conditions. The markers have the same meanings as in Fig. 3.

Fig. 6.

Results of detrended fluctuation analysis for the forces of the CTS and healthy subjects. (A) α_{DFA} of pinch force under visual and non-visual conditions. (B) α_{DFA} of the forces exerted by the thumb and index finger under visual and non-visual conditions. §Significant difference between the thumb and index finger ($p < 0.001$). †Significant difference between the visual and non-visual conditions ($p < 0.001$).

Fig. 7.

Inter-digit force correlation for the CTS and healthy subjects. (A) α_{DCCA} of pinch force under visual and non-visual conditions. (B) α_{DCCA} of the forces exerted by the thumb and index finger under visual and non-visual conditions. †Significant difference between the visual and non-visual conditions ($p < 0.001$).

Table 1

Characteristics of the CTS and healthy subjects.

Num total	CTS		Control												
	Sex	Age (y)	Maximal pinch force (N)	SWM score (1)	MHQ score (2)	LSQ score (3)	Motor		Sensory		Age (y)	Maximal pinch force (N)	SWM score	MHQ score	LSQ score
							Latency (ms)	CMAP (mV) (4)	Latency (ms)	SNAP (uV) (5)					
1	F	35	35.3	3.61/3.84	50.7	51	5.1	8.7	2.7	22.7	35	59.5	2.44/1.65	83.3	20
2	M	51	100.0	2.83/2.83	37.9	74	6.3	9	6	11.4	55	77.8	2.83/2.44	83.3	19
3	F	52	48.7	3.22/2.44	49.0	52	5.2	8	4.4	15	47	52.3	3.22/2.83	83.3	19
4	F	43	52.3	3.22/3.22	26.2	80	3.85	3.91	3	34.6	43	44.1	2.44/2.44	80.8	20
5	F	35	54.2	2.44/2.44	44.7	57	NA	NA	3.2	32.6	34	70.3	1.65/2.36	83.3	19
6	F	53	44.8	2.83/2.44	40.7	63	6.1	1.6	3.9	10.3	56	51.0	2.36/2.44	96.25	23
7	F	51	45.8	3.22/3.22	65.9	41	5	5.23	2.25	39.1	49	60.4	2.83/2.44	81.5	20
8	F	46	45.1	3.22/3.22	53.5	62	3	11.6	2.9	29.1	48	56.2	2.44/2.44	83.3	19
9	F	64	38.9	3.22/3.22	74.4	42	2.9	7.6	3.2	24.7	60	46.1	2.83/2.44	83.3	19
10	F	52	41.2	3.61/2.83	66.4	60	5.55	3.82	7.2	11.9	53	56.2	2.44/2.83	82.3	21
11	M	64	67.3	3.84/3.22	57.0	56	6.8	4.6	NA	NA	57	84.0	2.83/2.83	83.33	19
Mean		49.6	52.1	3.21/2.99	51.5	58	4.98	6.406	3.88	23.14	48.8	59.81	2.57/2.47	84.00	19.8
SD		9.6	18.1	0.40/0.44	14.1	11.9	1.34	3.05	1.58	10.59	8.6	12.70	0.41/0.33	4.16/0.328423	1.3

(1) SWM = Semmes Weinstein Monofilament. Scores were presented as thumb/index finger.

(2) MHQ = Michigan hand outcomes questionnaire.

(3) LSQ = Levine’s severity questionnaire. Data presented were the total score.

(4) CMAP = Compound motion action potential.

(5) SNAP = Sensory nerve action potential.