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BASIC RESEARCH

Is the Control of Applied Digital Forces During Natural Five-digit Grasping Affected by Carpal Tunnel Syndrome?

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Abstract

Background The impaired sensory function of the hand induced by carpal tunnel syndrome (CTS) is known to disturb dexterous manipulations. However, force control during daily grasping configuration among the five digits has not been a prominent focus of study. Because grasping is so important to normal function and use of a hand, it is important to understand how sensory changes in CTS affect the digit force of natural grasp.

Questions/purposes We therefore examined the altered patterns of digit forces applied during natural five-digit grasping in patients with CTS and compared them with those seen in control subjects without CTS. We hypothesized that the patients with CTS will grasp by applying larger forces with lowered pair correlations and more force variability of the involved digits than the control subjects. Specifically, we asked: (1) Is there a difference between patients with CTS and control subjects in applied force by digits during lift-hold-lower task? (2) Is there a difference in force correlation coefficient of the digit pairs? (3) Are there force variability differences during the holding phase?

Methods We evaluated 15 female patients with CTS and 15 control subjects matched for age, gender, and hand dominance. The applied radial forces (F_r) of the five digits were recorded by respective force transducers on a cylinder simulator during the lift-hold-lower task with natural grasping. The movement phases of the task were determined by a video-based motion capture system.

Results The applied forces of the thumb in patients with CTS (7 ± 0.8 N; 95% CI, 7.2–7.4 N) versus control subjects (5 ± 0.8 N; 95% CI, 5.1–5.3 N) and the index finger in patients with CTS (3 ± 0.3 N; 95% CI, 3.2–3.3 N) versus control subjects (2 ± 0.3 N; 95% CI, 2.2–2.3 N) observed throughout most of the task were larger in the CTS group (p ranges 0.035–0.050 for thumb and 0.016–0.050 for index finger). In addition, the applied force of the middle finger in patients with CTS (1 ± 0.1 N; 95%

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Each author certifies that his or her institution approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.
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CI, 1.3–1.4 N) versus the control subjects (2 $\pm$ 0.2 N; 95% CI, 1.9–2.0 N) during the lowering phase was larger in CTS group (p ranges 0.039–0.050). The force correlations of the thumb-middle finger observed during the lowering phase in the patients with CTS (0.8 $\pm$ 0.2; 95% CI, 0.6–0.9) versus the control subjects (0.9 $\pm$ 0.1; 95% CI, 0.8–1.0; $p = 0.04$) were weaker in the CTS group. The thumb-little finger during holding in the patients with CTS (0.5 $\pm$ 0.2; 95% CI, 0.3–0.7) versus the control subjects (0.8 $\pm$ 0.2; 95% CI, 0.6–0.9; $p = 0.02$), and the lowering phase in the patients with CTS (0.6 $\pm$ 0.2; 95% CI, 0.3–0.8) versus the control subjects (0.9 $\pm$ 0.1; 95% CI, 0.8–1.0; $p = 0.01$) also were weaker. The force variabilities of patients with CTS were greater in the CTS group than in the control subjects: in the thumb ([0.26 $\pm$ 0.11 N, 95% CI, 0.20–0.32 N] versus [0.19 $\pm$ 0.06 N; 95% CI, 0.16–0.22 N], $p = 0.03$); index finger ([0.09 $\pm$ 0.07 N; 95% CI, 0.05–0.13 N] versus [0.05 $\pm$ 0.03 N; 95% CI, 0.04–0.07 N], $p = 0.03$); middle finger ([0.06 $\pm$ 0.04 N; 95% CI, 0.04–0.08 N] versus [0.03 $\pm$ 0.01 N; 95% CI, 0.02–0.04 N], $p = 0.02$), and ring finger ([0.04 $\pm$ 0.03 N; 95% CI, 0.20–0.06 N] versus [0.02 $\pm$ 0.01 N; 95% CI, 0.02–0.02 N], $p = 0.01$).

Conclusions Patients with CTS grasped with greater digit force associated with weaker correlation and higher variability on specific digits in different task demands. These altered patterns in daily grasping may lead to secondary problems, which will need to be assessed in future studies with this model to see if they are reversible in patients undergoing carpal tunnel release.

Clinical Relevance The current results helped to identify altered patterns of grasping force during simulated daily function in patients with CTS and to provide the clinician with potential information that might help guide the rehabilitation of grasp in these patients.

Introduction

The hand receives sensory stimuli and performs motor commands [40] that are integrated in various functional manipulations required for daily tasks. Impairments to the sensory functions of the hand will cause disturbances to its fine motor performance. For instance, mechanical entrapment of the median nerve at the wrist region, which is known as carpal tunnel syndrome (CTS), results in numbness, pain, and weakness of the muscles innervated by the median nerve [6, 41]. CTS is more common among women than men, and can be caused by repeated or high-force manual tasks, especially from vocational exposure [22, 37]. As a result of symptoms caused by nerve abnormalities, patients with CTS face difficulties in various hand manipulations needed to perform daily activities, especially those requiring precision grasping [28].

Although clinical evaluations can quantitatively provide general indications regarding functional performance of the hand, the ability of fine force control may be missed by conventional assessments [2]. During the last decade, numerous devices have been used to record the forces applied by the digits during various grasp configurations [1, 21, 29, 39, 43, 45]. Studies show that patients with CTS exhibit diminished efficiency when pinching objects, implying that the affected digits are unable to accurately adjust the forces applied in response to the given external load [21, 29, 39]. As for five-digit grasping, several studies also examined the altered controls of grasping force with respect to grasping objects with different weights [45], changed center of masses [43], and various textures [1]. These studies indicated that patients with CTS grasped with excessive forces and showed an inability to discriminate weight accurately, performed less modulation of force despite changes in the center of mass, and poorly adjusted the forces applied across various textures. The force of each digit was coordinated with the forces from the other four digits and also adjusted to achieve the requirements of the task, such as the observed different patterns between vertical lifting and rotating a cup [8]. As a result, the altered coordination among digits or the compensatory role of each digit in patients with CTS should be addressed, rather than the overall grip force.

Force variability has been used to quantify the stability control of digit force, thus serving as an indicator of precision performance [7, 27]. Greater variability of digit force was observed in men compared with women [14], in the nondominant hand compared with the dominant [13], and in the elderly (60–69 years) compared with the young (20–29 years) [38]. However, few studies have examined how abnormal sensory functions affect force variability [9, 27], especially during five-digit grasping [45]. The synergies among the various roles of the fingers, which are described by the force relationships among thumb-finger pairs [8, 24, 36], may provide insights into the coordination that occurs among the involved and intact digits of patients with CTS. In addition to the altered patterns of grasping force in patients with CTS, the patterns of force applied also depend on the contact positions of the digits during grasping, especially the thumb [8, 21, 25, 43, 45]. To assess how the impairments resulting from CTS affect daily grasping, the natural grasping configuration of patients should be considered in an experimental setting [11, 30].

The aim of our study therefore was to compare the control characteristics of digit forces during five-digit cylindrical grasping by patients with CTS and a group of control subjects without CTS. We hypothesized that the patients with CTS would grasp by applying larger forces with lowered pair correlations and more force variability of the involved digits than the control subjects. Specifically, we asked: (1) Is there a difference between patients with CTS and control subjects in applied force among the digits during lift-hold-lower task? (2) Is there a difference in force correlation coefficients of the digits? (3) Are there force variability differences during the holding phase?

Patients and Methods

Participants

To eliminate the effects of age, gender, and hand dominance on the control of digit forces [9], right-handed female subjects between the ages of 35 and 74 years were recruited and their right hands were evaluated for both groups. Fifteen female patients, who had a diagnosis of CTS in the right hand, participated in this study. The patients who had a diagnosis of idiopathic CTS of the right hand who met the inclusion criteria, which included impaired sensory and intact motor functions of the median nerve by nerve conduction velocity examination, female gender, and right hand dominance, were considered for inclusion in the study. Patients were excluded if they could not perform the testing task correctly, such as failure to grasp safely or slip occurred owing to the severely impaired sensation. We selected 15 eligible patients to participate in this study and completed the experiments.

Patients received nerve conduction examination to confirm that they had involvement of the sensory function of the median nerve only and to exclude those whose ulnar nerve and motor function of the median motor nerve were affected (Table 1). Fifteen healthy age-matched females were recruited from the community as the control group. Participants were excluded if they had a history of stroke, diabetes, cervical radiculopathy, other sensory disorders, or musculoskeletal disorders of the right wrist and hand. Participants were informed of the purpose and procedures of this study and signed consent forms approved by the institutional review board.

Instruments

The sensory and motor nerve conduction examinations in patients were performed by using Medelec Synergy™ N-EP EMG apparatus (Oxford Instruments Medical, Inc, Abingdon, UK). A custom cylindrical simulator was designed with five force transducers (Nano-25 and Nano-17s; ATI Industrial Automation, Apex, NC, USA) to record the applied digit forces with a sampling rate of 800 Hz (Fig. 1). One transducer (Nano-25) was set for the thumb and the other four (Nano-17) were for the index, middle, ring, and little fingers. The force data recorded by the transducers were transmitted through a 16-bit A/D converter (i430; GW Instruments, Charlestown, MA, USA) and stored in a computer. Each transducer was covered with an aluminum saddle-like cap with a curved convex surface, with a 33-mm radius of curvature to form the outer circumference of the cylinder. The positions of the force transducers could be adjusted according to each participant's grasping configuration. The mapping matrix from voltage to Newton was obtained according to the product specification from ATI. Before this study, we checked the accuracy of these sensors in our laboratory by a series of standard weights within the level of tolerance. Before beginning every experiment, the baseline output voltage was mapped to zero by subtracting the default voltage in each channel. The digit force applied on the transducer in the normal direction was represented by the radial force (F_r) and analyzed in the current study. A video-based motion capture system with eight cameras (Eagle System, EGL-500RT; Motion Analysis Corporation, Santa Rosa, CA, USA) was used to record the dynamic position of the simulator during testing for determination of task phases, with a sampling rate of 100 Hz. The coordinate system of the simulator was defined by three reflective markers attached to the top plate: the first and second markers were aligned with the force transducer for the thumb and index finger, respectively, and the third marker was on the intersection of the circumference and line perpendicular to the line between the first and second markers.

Nerve Conduction Examination

The temperature of the laboratory and the skin of the upper extremity of the patient was maintained at 23° to 26° and 32 °C, respectively. Three different sites, including the palm, wrist, and elbow, were selected for stimulating the median nerve with the surface recording ring electrodes on the index finger [34]. The amplitude of the sensory nerve action potential during stimulation at the wrist, the peak distal latency of sensory nerve action potential recorded during stimulation at the wrist, and conduction velocity in the segment from the wrist to the palm were used to represent the response of the sensory nerve.

Experimental Procedure

The participants were first asked to clean their digit pads with alcohol swabs. The resting position of the subject was to sit upright on a height-adjustable chair with the upper arms against the side of the body and forearms resting on

Table 1. Demographic data of nerve conduction examination on median and ulnar nerve in patients with CTS

Patient number	Occupation	Age (years)	Nerve	Amplitude (V for sensory, μV for motor)	Velocity (m/second)	Latency (ms)
1	Housewife	41	Median sensory	4.2	37.7	3.7
			Median motor	6.8	47.4	4.2
			Ulnar sensory	14	45.4	2.3
2	Accountant	35	Median sensory	8	32	4.5
			Median motor	6.2	63	3.4
			Ulnar sensory	19	62	2.0
3	Porter	60	Median sensory	35	34	2.9
			Median motor	4	54	3.6
			Ulnar sensory	18	48	2.4
4	Teacher	53	Median sensory	14	42	3.3
			Median motor	6.4	62	4.1
			Ulnar sensory	17	53	2.0
5	Cleaner	39	Median sensory	14	36	3.7
			Median motor	7.4	55	3.4
			Ulnar sensory	14	51	2.4
6	Cook	55	Median sensory	9	23	5.9
			Median motor	4.9	57	3.6
			Ulnar sensory	13	49	2.2
7	Packer	48	Median sensory	14	38	3.5
			Median motor	7.6	55	3.7
			Ulnar sensory	14	51	2.3
8	Manual manufacturer	43	Median sensory	2	28	5.2
			Median motor	8.8	53	4.7
			Ulnar sensory	12	59	2.1
9	Housewife	61	Median sensory	21	39	3.7
			Median motor	6.5	52	3.8
			Ulnar sensory	16	60	2.2
10	Housewife	74	Median sensory	4.2	26.5	5.0
			Median motor	4	48	3.9
			Ulnar sensory	17	47	2.5
11	Cook	48	Median sensory	4	67	2.3
			Median motor	4.3	59	4.2
			Ulnar sensory	22	60	2.0
12	Housewife	65	Median sensory	4.6	23.3	4.8
			Median motor	5.9	50	3.7
			Ulnar sensory	14.2	42	2.2
13	Housewife	53	Median sensory	2.5	22	5.0
			Median motor	4.4	57	4.2
			Ulnar sensory	16	55.8	2.4
14	Housewife	66	Median sensory	2.6	19.3	5.7
			Median motor	4.6	52	4.4
			Ulnar sensory	14	56	2.0
15	Dressmaker	55	Median sensory	2	21	5.2
			Median motor	5	50	4.1
			Ulnar sensory	16	95	3.0

CTS = carpal tunnel syndrome.

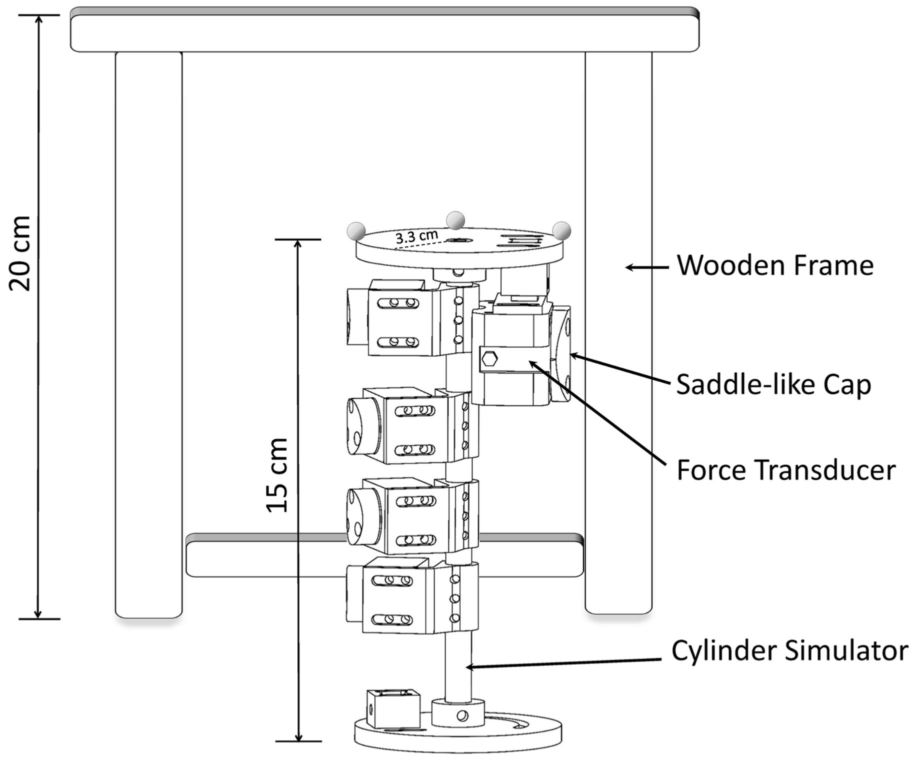

Fig. 1 The cylinder simulator apparatus (height, 15 cm; weight, 390 g) with five force transducers which were adjustable to natural grasping configuration, was used to record the applied forces of digits. The movement of the simulator was represented by the three markers on the top. A wooden frame was used to guide the height of lifting.

the table in front (Fig. 2). The simulator was located at the midline of the participant at a distance of her forearm length. Before data recording, the participants were asked to grasp the simulator in their usual way so that the positions of the transducers could be adjusted until each digit pad could comfortably contact the center of its respective transducer. The testing tasks were performed by using minimal force at the subject's self-selected speed, and the participants were allowed to familiarize themselves with the apparatus and tasks. Three successful trials were required, and a trial would be restarted if any errors occurred. The testing movement of the lift-hold-lower task was done with the following steps: grasping and lifting the simulator upward and vertically to the height of 20 cm, then holding it in the air for at least 3 seconds, and finally lowering it to the original place (Fig. 3). The target height of 20 cm was guided by a wooden frame (Figs. 1 and 2). All participants underwent clinical sensory evaluations on the digits innervated by the median nerve, including the two-point discriminative test and the Semmes–Weinstein monofilaments test. There were no differences between the control subjects and CTS group regarding age (56 ± 6 years [range, 47–65 years] and 53 ± 11 years [range, 35–74 years], $p = 0.401$), height (157 ± 5 cm and 155 ± 4 cm, $p = 0.337$), body weight (56 ± 7 kg and 60 ± 11 kg, $p = 0.190$) and hand size (palm length, 93 ± 5 mm [95% CI, 90–96 mm] and 90 ± 10 mm [95% CI, 84–95 mm], $p = 0.281$; palm width, 76 ± 3 mm [95% CI, 74–78 mm] and 74 ± 7 mm [95% CI, 70–78 mm], $p = 0.281$). The digits innervated by the median nerve showed impaired sensory functions in the patients with CTS compared with the control subjects on the two-point discriminative test (5 ± 1 mm and 4 ± 0.8 mm, $p < 0.001$; 6 ± 2 mm and 4 ± 0.4 mm, $p < 0.001$; 6 ± 1 mm and 4 ± 1 mm, $p < 0.001$; 5 ± 0.9 mm and 4 ± 0.9 mm, $p < 0.001$; for the thumb, index, middle and ring fingers, respectively) and Semmes–Weinstein monofilaments test (0.49 ± 0.58 g and 0.07 ± 0.09 g, $p = 0.009$; 0.41 ± 0.48 g and 0.06 ± 0.10 g, $p = 0.008$; 0.36 ± 0.43 g and 0.06 ± 0.09 g, $p = 0.016$; 0.24 ± 0.35 g and 0.04 ± 0.03 g, $p = 0.042$; for the thumb, index, middle, and ring fingers, respectively). However, the little finger of patients with CTS also showed the retarded response on the two-point discriminative test (5 ± 0.8 mm versus 4 ± 1 mm, $p = 0.001$), but not in the Semmes–Weinstein monofilaments test with the numbers available (0.26 ± 0.40 g versus 0.06 ± 0.09 g, $p = 0.072$). The maximal strength of the evaluated hand also was measured based on the grasp of the tip pinch and three-jaw chuck pinch using a pinch gauge (PG-30; Pinsco, Inc, Santa Ana, CA, USA) and power grip using a hand dynamometer (Jamar® Plus+; Patterson Medical,

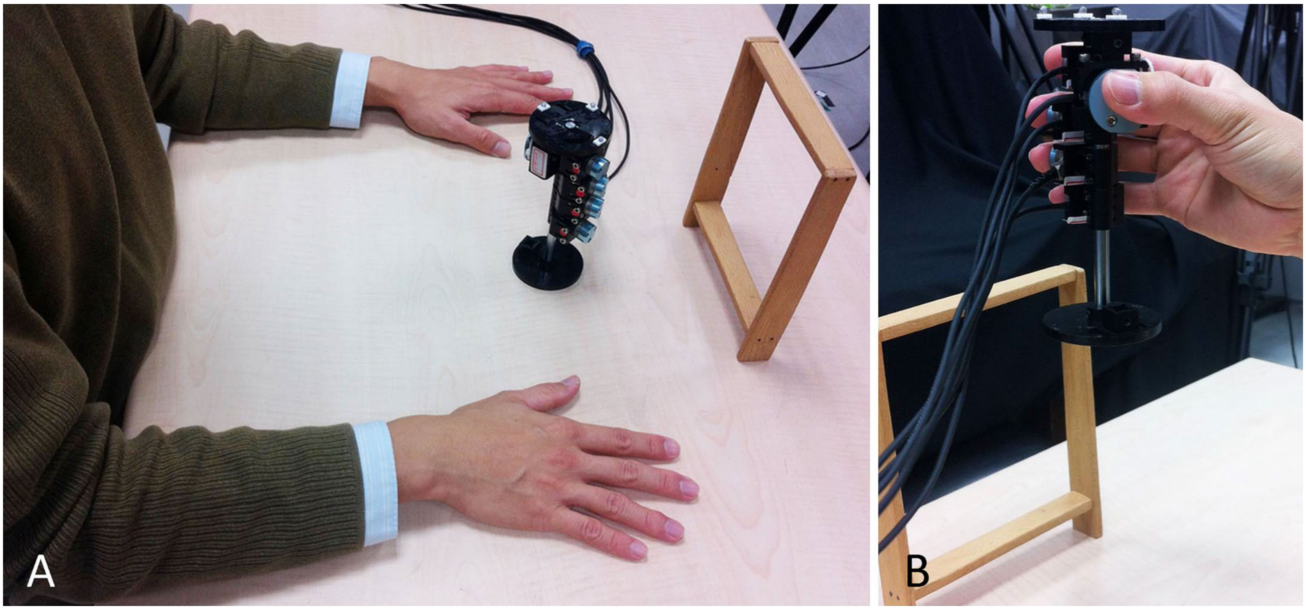

Fig. 2A–B (**A**) Each subject sat upright with the forearms resting on the table in front and the simulator was located at the midline at a distance of forearm length. (**B**) The lift-hold-lower task was performed by grasping and lifting the simulator upward and vertically to the height of 20 cm, then holding it in the air for at least 3 seconds, and finally lowering it to the original place.

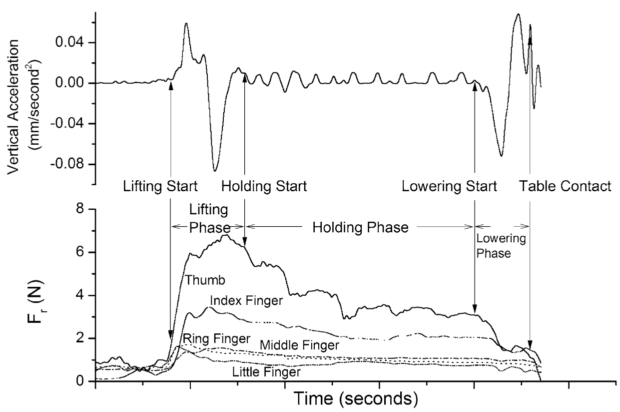

Fig. 3 The definitions of the four events (lifting start, holding start, lowering start, and table contact) and three phases (lifting, holding, and lowering phases) were based on the vertical acceleration during the lift-hold-lower task.

Warrenville, IL, USA). The patients with CTS had weaker maximal grip force than the control subjects (14 ± 6 kg and 23 ± 5 kg, $p < 0.001$), whereas there were no differences, with the numbers available, in the maximal force of tip pinch (6 ± 3 kg and 5 ± 1 kg, $p = 0.337$) and three-jaw chuck tests (6 ± 3 kg and 6 ± 1 kg, $p = 0.587$).

Data Analysis and Statistics

According to the acceleration of the simulator in the superoinferior direction, calculated by differentiating the position data of the geometric centers of three markers (Fig. 1), the movement sequences of the lift-hold-lower task can be determined by specific movement events (lifting start, holding start, lowering start, and table contact) and separated into two transient phases (lifting and lowering phases) and one steady phase (holding phase).

All the force data were filtered by a low-pass Butterworth filter (fourth order with a cutoff frequency of 10 Hz) before further analysis. To compare the amplitude of applied F_r throughout the task between groups, the averaged digit F_r in each group was obtained after resampling the raw digit F_r of each trial to 100 points per phase. The mean value of F_r at every resampling point in each group then was computed. The force correlations of the four thumb-finger pairs (thumb-index finger, thumb-middle finger, thumb-ring finger, and thumb-little finger) were analyzed throughout the task for each participant. To discover the changes in the correlation patterns between groups, the coefficients of force pairs were transformed through Fisher's Z-transformation to the normal distribution values for further computations. The force variability of each digit was evaluated by the root mean square value (RMS_{fv}) of the difference between the applied F_r and its predicted value based on the fitting line by the first-order polynomial regression method during the holding phase.

The Pearson correlation coefficient was used to quantify the force correlation of thumb-finger pairs. The differences in the clinical evaluations and force parameters between the groups were measured by independent t-tests. In addition, one-way ANOVA was conducted to assess the effects

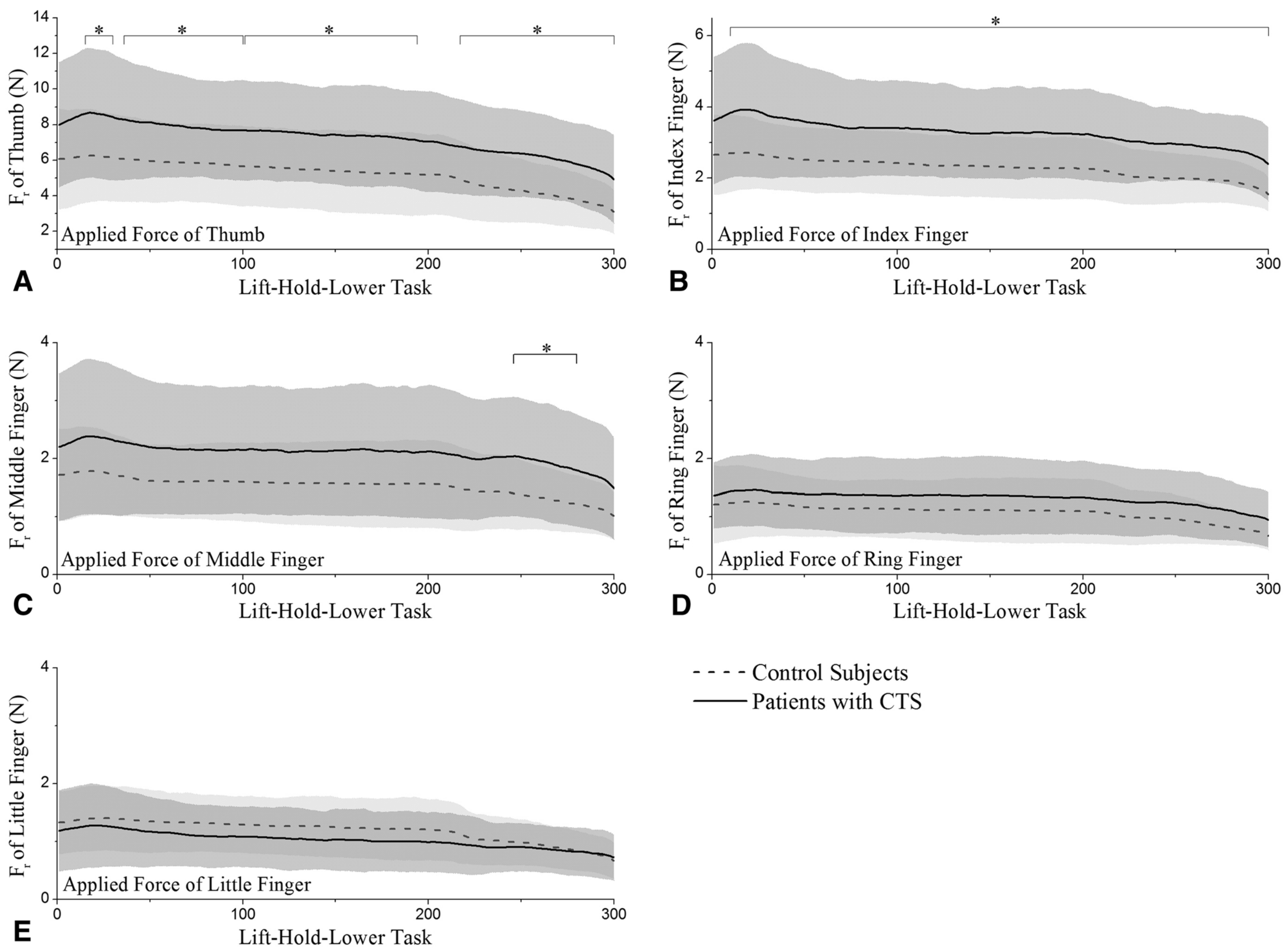

Fig. 4A–E The averaged digit F_r for (**A**) the thumb, and the (**B**) index, (**C**) middle, (**D**) ring, and (**E**) little fingers throughout the lift-hold-lower task were obtained by resampling the data to 100 points per phase (1st–100th percentile, lifting phase; 101st–200th percentile, holding phase; 201st–300th percentile, lowering phase). The dashed line with light gray represents the values of the means and SDs of F_r for the control subjects and the solid line with dark gray is for the CTS group. *Significant differences between the digit F_r for the control subjects and CTS groups at specific data points: the 15th to 30th, 36th to 100th, 101st to 194th, and 217th to 300th percentiles of the thumb F_r; the 10th to 300th percentile of the index finger F_r; and the 246th to 280th percentile of the middle finger F_r ($p < 0.05$). CTS = carpal tunnel syndrome.

of various task phases on the patterns of force correlation and the post hoc test was performed using the least significant difference. The Pearson correlation coefficient also was used to find the relationships between the variability in force and levels of applied force in both groups. All the analytic processes were performed using MATLAB® (MathWorks, Inc, Natick, MA, USA) and SPSS 17.0 (SPSS Inc, Chicago, IL, USA) software. The statistical significance was set at a probability less than 0.05.

Results

The Applied F_r

The trace of each digit F_r was generally not different with the numbers available between groups, but the statistical results indicated that the applied F_r of the thumb and index finger among the patients with CTS were greater than those of the control subjects throughout most of the task (Fig. 4); mean F_r across three phases (thumb: 7 ± 0.8 N [95% CI, 7.2–7.4 N] and 5 ± 0.8 N [95% CI, 5.1–5.3 N], $p < 0.001$; index finger: 3 ± 0.3 N [95% CI, 3.2–3.3 N] and 2 ± 0.3 N [95% CI, 2.2–2.3 N], $p < 0.001$). A larger F_r of the middle finger for the patients with CTS also occurred during the last 1/2 of the lowering phase (mean F_r during lowering phase, 2 ± 0.2 N [95% CI, 1.9–2.0 N] and 1 ± 0.1 N [95% CI, 1.3–1.4 N], $p < 0.001$). There were no differences with the numbers available between the CTS group and control subjects regarding the F_r of the ring finger (mean F_r across three phases, 1.3 ± 0.1 N [95% CI, 1.3–1.3 N] and 1.1 ± 0.1 N [95% CI, 1.1–1.1 N]) and little finger (mean F_r across three phases, 1 ± 0.1 N [95% CI, 1.0–1.0 N] and 1.2 ± 0.2 N [95% CI, 1.2–1.2 N]).

Table 2. Means (SDs) of the correlation coefficients between the F_r of the thumb and each of four fingers in three phases

Phases	Thumb-index finger	Thumb-middle finger	Thumb-ring finger	Thumb-little finger
Lifting				
Control subjects	0.90 (0.12)	0.82 (0.16)	0.85 (0.15)§	0.75 (0.18)¶
Patients with CTS	0.86 (0.14)	0.69 (0.20)	0.64 (0.21)	0.67 (0.21)
Holding				
Control subjects	0.77 (0.18)	0.59 (0.22)‡	0.45 (0.25)§,‖	0.75 (0.18)**
Patients with CTS	0.73 (0.19)†	0.48 (0.24)	0.64 (0.21)	0.51 (0.24)*
Lowering				
Control subjects	0.87 (0.15)	0.92 (0.12)‡	0.90 (0.13)‖	0.90 (0.13)¶,**
Patients with CTS	0.89 (0.14)†	0.77 (0.19)*	0.79 (0.18)	0.63 (0.23)*

CTS = carpal tunnel syndrome; *significantly lower coefficient in patients with CTS than control subjects for thumb-little finger during holding and lowering phases and thumb-middle finger during lowering phase; †significant differences between thumb-index finger correlation of patients with CTS during holding and lowering phases; ‡significant differences between thumb-middle finger correlation of control subjects during holding and lowering phases; §significant differences between thumb-ring finger correlation of control subjects during lifting and holding phases; ‖significant differences between thumb-ring finger correlation of control subjects during holding and lowering phases; ¶significant differences between thumb-little finger correlation of control subjects during lifting and lowering phases; **significant differences between thumb-little finger correlation of control subjects during holding and lowering phases.

The Force Correlations of Digit Pairs

The CTS group showed smaller correlation coefficients of the thumb-finger pairs than the control subjects on the thumb-little finger during the holding phase (0.5 ± 0.2 [95% CI, 0.3–0.7] and 0.8 ± 0.2 [95% CI, 0.6–0.9], $p = 0.023$) and lowering phase (0.6 ± 0.2 [95% CI, 0.3–0.8] and 0.9 ± 0.1 [95% CI, 0.8–1.0], $p = 0.010$) and the thumb-middle finger (0.8 ± 0.2 [95% CI, 0.6–0.9] and 0.9 ± 0.1 [95% CI, 0.8–1.0], $p = 0.038$) during the lowering phase (Table 2). Regarding the effect of different phases of the task, the results indicated that the correlations of the thumb-middle finger ($F_{2,12} = 6.07$, $p = 0.005$), thumb-ring finger ($F_{2,12} = 6.07$, $p = 0.002$), and thumb-little finger ($F_{2,12} = 3.46$, $p = 0.041$) in the control subjects and the thumb-index finger ($F_{2,12} = 3.46$, $p = 0.015$) in the CTS group were associated with the demands made in each of the phases. The post hoc test by least significant difference revealed smaller coefficients at the holding phase than the lowering phase on the thumb-middle finger (holding, 0.6 ± 0.2 [95% CI, 0.3–0.8]; lowering, 0.9 ± 0.1 [95% CI, 0.8–1.0], $p < 0.001$), smaller at the holding phase than the lifting and lowering phases on the thumb-ring finger (lifting, 0.9 ± 0.2 [95% CI, 0.7–0.9]; holding, 0.5 ± 0.3 [95% CI, 0.1–0.7]; lowering, 0.9 ± 0.1 [95% CI, 0.8–1.0]; $p = 0.007$ and $p < 0.001$), and larger at the lowering phase than the lifting and holding phases on the thumb-little finger (lifting, 0.8 ± 0.2 [95% CI, 0.6–0.9]; holding, 0.8 ± 0.2 [95% CI, 0.6–0.9]; lowering, 0.9 ± 0.1 [95% CI, 0.6–0.9]; $p = 0.027$ and $p = 0.029$) in the control subjects. However, in the CTS group, only a weaker relationship of the thumb-index finger in the holding phase compared with that in the lowering phase was seen (holding, 0.7 ± 0.2 [95% CI, 0.6–1.2]; lowering, 0.9 ± 0.1 [95% CI, 0.8–0.9]; $p = 0.015$).

The Force Variability During the Holding Phase

The results showed that the RMS_{fv} of the thumb, index, middle, and ring fingers in the patients with CTS were larger than in the control subjects (thumb, 0.26 ± 0.11 N [95% CI, 0.20–0.32 N] and 0.19 ± 0.06 N [95% CI, 0.16–0.22 N], $p = 0.037$; index finger, 0.09 ± 0.07 N [95% CI, 0.05–0.13 N] and 0.05 ± 0.03 N [95% CI, 0.04–0.07 N], $p = 0.040$; middle finger, 0.06 ± 0.04 N [95% CI, 0.04–0.08 N] and 0.03 ± 0.01 N [95% CI, 0.02–0.04 N], $p = 0.014$; ring finger, 0.04 ± 0.03 N [95% CI, 0.02–0.06 N] and 0.02 ± 0.01 N [95% CI, 0.02–0.02 N], $p = 0.008$), although no difference was observed regarding the little finger (0.04 ± 0.04 N [95% CI, 0.02–0.06 N] and 0.03 ± 0.02 N [95% CI, 0.02–0.05 N], $p = 0.544$) with the numbers available. Furthermore, in the patients with CTS, direct correlations between RMS_{fv} and the mean F_r of the holding phase were found in the index ($r = 0.66$, $p = 0.007$), middle ($r = 0.83$, $p < 0.001$), and little ($r = 0.71$, $p = 0.003$) fingers (Fig. 5). However, such relationships between RMS_{fv} and averaged F_r were absent in the control subjects.

Discussion

Without intact sensory feedback from the median nerve distribution, the precision grasp function is limited to some extent in patients with CTS. The forces applied by patients with CTS therefore are excessive and unable to precisely meet the needs of the task. However, the ability to control digit forces in the functional grasping configuration has not been reported in very many studies [21, 23, 29, 42–45]. We therefore examined the deficiencies in digit force control during five-digit grasping in patients with CTS. We found that the patients grasped by higher digit force, weaker correlation, and higher variability on specific digits than the control subjects. This suggests the sensory impairment of CTS affected the coordination of digit forces during natural grasping, even though the minimal force and self-selected speed were requested to grasp the simulator for the simple task.

This study has some limitations regarding our finding on the ability to control digits. First, although impairments to sensory functions and force patterns may be associated with the duration of nerve irritation, the actual duration of CTS often is unknown by patients because it is a gradual process. Second, we did not quantify hand activities used in activities of daily living. More practice of dexterous manipulation may enhance the force control ability and strengthen the intrinsic muscles. Third, because of the high incidence of CTS in females, only female patients were recruited in this study. To simplify the problem caused by impaired sensory function, mild to moderate CTS was studied since severe CTS may affect motor function profoundly and the patient might be unable to perform the task completely. Therefore our results might not be able to be generalized to male patients or patients with severe CTS. Fourth, some study variables without differences between groups might have been caused by the small number of participants, such as the differences between groups for applied force and force correlation being noticed only during some phases. Finally, the poor response of the little finger to sensory evaluation was seen in some of the patients with CTS, although the patients with impaired ulnar nerve functions and with radiculopathy had been excluded. Paresthesia of the little finger in patients with CTS, which may be attributable to increased pressure in Guyon's canal transmitted from the high carpal tunnel pressure via the transverse ligament, has been seen in patients with mild CTS [5, 16–18]. Despite the smaller contribution from the little finger to the lift-hold-lower task we observed and as reported in a previous study [8], it may be worthwhile to investigate the effects on force control in patients with impaired sensation on little finger to further clarify the role of the little finger during five-digit grasping.

The patients with CTS exerted more F_r of the thumb and index finger throughout the task, and on the middle finger during the lowering phase, than that seen in the control group. This is similar to previous observations that patients with CTS grasp objects with excessive force in various configurations [1, 29, 39, 42, 45]. This inefficiency of applied force is attributed to the impaired cutaneous sensation of the digits, because the pinch efficiency improved with recovery of sensory functions after carpal tunnel release [21]. However, it was difficult for the patients with CTS to grasp with five digits rather than pinching, because the former required coordination among five digits which included the intact digits and those affected by CTS [26, 44]. By assessing the relationship between applied force during grasping and the sensory status of each digit across patients and controls, only weak correlations between two-point discrimination and applied force on the thumb ($r = 0.392$, $p = 0.032$) and ring finger (0.436, $p = 0.016$) were seen. Our assessment revealed that any alteration of each digit force will cause interdigit compensation during grasping by multiple digits, rather than intradigit behavior. We also observed this altered coordination in patients with CTS in maximal strength evaluations. The patients showed decreased power grip strength compared with the control subjects while the strengths of the tip and three-jaw chuck pinch were preserved. The decreased strength of the power grip may be attributable to the ability of patients with CTS to do synchronous maximal exertion either from all of the digits, including the intact and involved digits, or the intrinsic and extrinsic muscles [15, 23]. Furthermore, the index and middle fingers and the thumb contributed more than the other digits to the total grasping force during the natural grasping configuration [8]. The patients with CTS adopted compensatory strategies mainly by augmenting the forces of these three most important digits to perform daily tasks, which may lead to the cumulative overloading to the musculotendons and to secondary injuries. It is common to see the development of trigger digits in patients with idiopathic CTS especially after carpal tunnel release [19, 20, 35]. Therefore, the pattern of applied digit force with CTS should be kept in mind for the clinician to educate patients and for the researcher to examine the possible pathomechanics.

Although the force synergy of the thumb and fingers during multidigit grasping obeys the simple patterns of pair relationships, the patterns vary depending on the tasks performed and the related grasping configurations and impairments of the hand [8, 24, 36]. The decreased correlations seen in the patients with CTS may be because the F_r of the thumb and opposite finger were adjusted in a nonsynchronous manner, which was observed as the mismatched tendency in the changes in force. From a neurophysiologic perspective, the electromyographic coherence of pair muscles, which varies across digits and implies that neural inputs from the central controller drive the engaged digits by coordinating the related digital muscles, may be altered in specific digits in patients with CTS [12, 32]. In addition, our patients with CTS showed few alterations of pair correlations with respect to the phase

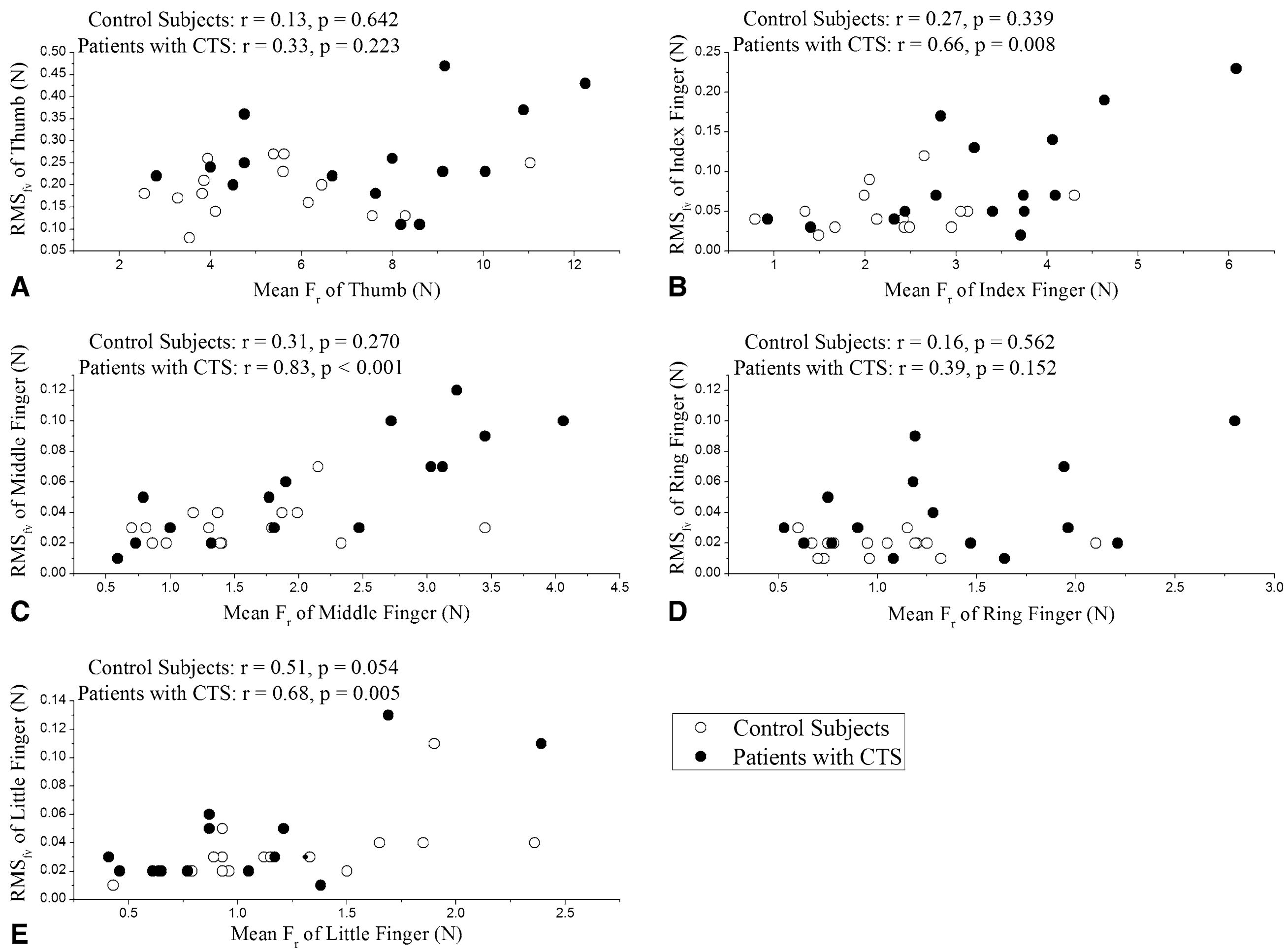

Fig. 5A–E The relationships between force variability (RMS$_{fv}$) and mean applied force (F$_r$) during the holding phase are shown for the (**A**) thumb, and (**B**) index, (**C**) middle, (**D**) ring, and (**E**) little fingers. The significant correlations were found only in the patients with CTS on the (**B**) index, (**C**) middle and (**E**) little fingers, but no correlation was seen in the control subjects. CTS = carpal tunnel syndrome.

changes. The task-dependent patterns of five-digit grasping have been examined from the perspectives of kinematics and kinetics, and these are coordinated according to the different requirements of the tasks such as the end position or mass of an object [4, 10, 11, 21, 30, 33]. During lifting and lowering, more emphasis regarding control of the digits' forces should be placed on acceleration and deceleration of objects. Therefore, strong corresponding relationships of the finger-thumb pairs may have been required to move the simulator and prevent it from overshooting the target height during lifting or impacting the table during the lowering phase in the current study. The patients with CTS had an increased thumb-index finger correlation only during the lowering phase, which may be because the central controller minimized the degree of freedom by augmenting the relative roles of the thumb and index finger [25]. Furthermore, reorganization of the brain structures was found to correlate with the nerve conduction velocity in patients with CTS, and this was thought to be a secondary adaption to the peripheral nerve impairments [31]. However, more research is needed to link the relationships between the motor performance of the distal hand and central neural activities to verify the related control mechanism. The decreased force correlation with less adjustment to the changes of task demand in patients with CTS may retard the performance of an advanced precise task, such as with a hand tool used during surgery.

In the current study, the predominant force variability of the first four digits (thumb, index, middle, and ring fingers) in patients with CTS may be attributable to their insufficient awareness of the amount of applied forces required owing to the impaired sensory functions. Furthermore, we found that the variability increased along with the applied force in the index, middle, and little fingers of the patients with CTS. Although this was observed only in three digits, this finding is similar to the results of previous studies which reported that the variability of pinch force correlated with the force level in healthy subjects [14, 32]. Because the lift-hold-lower task was performed using the participants' self-selected minimal forces, and without the assistive guide of an applied force, the variability represented the force adjustments needed to achieve efficient exertion and to maintain the equilibrium of the simulator. If considering the force level during the holding phase by normalizing the sum of F_r from the five digits to the maximal grip force, holding the simulator was more demanding for the patients with CTS than for the control subjects. The reason why no trend of correlation was noticed in control subjects may be because the applied force and associated force variability of each digit in this group were controlled in a smaller range than that seen in the patients with CTS [3]. Additional studies are required to investigate the control mechanism of force variability across ranges of force levels during five-digit grasping. The measurement of force variability established in our study can be used to quantify the stability control of digit force and applied in other populations.

We found that higher digit force was associated with weaker correlation and higher variability in specific digits in patients with CTS than in the control subjects. Although it was known that the sensory impairment disturbed the digit force application, the applied force during natural grasping can represent how the patients grasped during daily activities. Future studies might consider following these findings to determine whether the altered pattern changes after carpal tunnel release, and to examine the relationship between trigger digit and applied digit forces in patients after carpal tunnel release. The presented findings may help us appreciate the altered pattern of grasping force in daily function and provide the clinician with information that may help design a rehabilitation program for patients with similar carpal tunnel syndrome.

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