Effect of Fatigue on Grip Force Control During Object Manipulation in Carpal Tunnel Syndrome

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Eight subjects with carpal tunnel syndrome (CTS) (47.13 ± 7.83 years) and 8 matched controls (46.29 ± 7.27 years) manipulated a test object fitted with an accelerometer and force sensor, both before and after hand muscle fatigue. Grip force and object acceleration were recorded and used to calculate grip force control variables that included Grip Force Peak, Safety Margin, and Time to Grip Force Peak. Individuals with CTS exhibited a higher Safety Margin (p = .010) and longer Time to Peak of Grip Force (p = .012) than healthy controls during object manipulation. Once fatigued, both groups significantly decreased their grip force to perform the task (Grip Force Peak; p = .017 and Safety Margin; p < .001). Nevertheless, individuals with CTS maintained an unnecessarily high safety margin. Our results suggest that CTS can adversely affect how the central nervous system regulates grip force, which might aggravate the inflammatory process and exacerbate the symptoms of this disease.

Keywords: hand function; grasp force; object manipulation; sensory deficit.

Grasping and lifting objects successfully involves applying grip force (horizontal force) to the object’s surface that is great enough to prevent it from slipping, yet not so great that the object is damaged. Such control of grip force is a complex process that combines feed-forward and feedback components of motor control. Grip force usually is regulated based upon certain mechanical characteristics of the manipulated object, such as its weight and shape, and the coefficient of friction that exists between the object’s contact surface and the person’s fingertips (Nowak & Hermsdörfer, 2003a; Westling & Johansson, 1984). While gripping and lifting an object, one’s grip force is economically and simultaneously modulated in parallel with variations in the object’s load force (tangential force, vertical to the surface) which, in turn, depends upon the object’s weight and acceleration. Therefore, grip
and load forces are coupled, in terms of time and magnitude, during dynamic manual tasks.

Moreover, the grip force used to secure an object in a static position usually exceeds the minimal force required to prevent it from slipping (slip force). The quantity of grip force that one applies to an object beyond the minimum force necessary to prevent it from slipping is known as the Safety Margin, which is calculated as the quantitative difference between the static and slip forces (Augurelle, Smith, Lejeune, & Thonnard, 2003; Blennerhassett, Carey, & Matyas, 2006; Dun, Kaufmann, & Li, 2007; Nowak, Glasauer, Meyer, Mai, & Hermsdörfer, 2002).

Several factors might influence grip force control when objects are handled. For example, sensory feedback from the fingertips plays a crucial role in the coordination of grip and load forces, which is important in ensuring a stable grasp during object manipulation (Augurelle et al., 2003; Hermsdorfer & Blankenfeld, 2008; Nowak & Hermsdörfer, 2003b; Westling & Johansson, 1984; Witney, Wing, Thonnard, & Smith, 2004). Patients with sensory deficits in the fingertips usually exhibit a substantial increase in both dynamic and static grip force (Fellows, Ernst, Schwarz, Töpper, & Noth, 2001; Hermsdorfer & Blankenfeld, 2008; Schenker, Burststedt, Wiberg, & Johansson, 2006; Witney et al., 2004). One disease that leads to decreased sensation in the fingertips is carpal tunnel syndrome (CTS), a common disorder associated with compression or other irritation of the median nerve as it passes through the carpal tunnel of the wrist (Radwin, Wertsch, Jeng, & Casanova, 1991; Szabo, Slater Jr., Farver, Breger, Stanton, & Sharman, 1999). Over the course of compression, A-beta nerve fibers are injured first, followed by C fibers, an order that corresponds with CTS symptoms (Tamburin et al., 2011; Nishimura et al., 2004). CTS often causes a range of symptoms that include numbness, tingling, and pain involving the fingers on the radial aspect of the hand (Agabegi, Freiberg, Plunkett, & Stern, 2007b).

Even though motor impairments are self-perceived by individuals with CTS during manual activities of daily living (Geere, Chester, Kale, & Jerosch-Herold, 2007), studies evaluating grip force control in these individuals during object manipulation are scarce. Thonnard and colleagues (1999) demonstrated that patients with CTS are able to obtain information about the level of friction between their skin and an object’s contact surface during lifting tasks and modify their pinch force accordingly. While this information is important, it remains unknown how grip force is controlled in individuals with CTS relative to healthy individuals.

Individuals with CTS usually complain about ‘tiredness’ in their hand or forearm, or fatigue while performing manual tasks (Dobkin, 2008; Rainoldi, Gazzoni, & Casale, 2008). Fatigue is an acute adaptation of the neuromuscular system and can contribute to impaired performance (Enoka & Stuart, 1992). For instance, studies by Danion et al. (2001) have demonstrated changes in finger coordination during manual tasks once muscle fatigue has set in. Although fatigue and weakness are well-known clinical characteristics of CTS, the fatigue-related changes in grip force control these patients remain noninvestigated.

Thus, in this study, we aimed to examine how individuals with CTS control their grip force during object manipulation, both in normal conditions and after fatigue has been induced in their hand. We hypothesized that individuals with CTS would demonstrate an unnecessarily high magnitude of grip force, relative to controls, and that fatigue would modify their grip force control. To test these hypotheses, individuals with CTS and matched healthy controls were instructed
to grasp a test object that had been fitted with both an accelerometer and a force sensor, and then to lift it vertically from a table before and after undergoing a hand fatigue protocol. Knowledge of how patients with CTS control their grip force during manipulation of objects may be useful in the neuro-rehabilitation field. In addition, clarifying whether fatigue induces changes in grip force control is important to better understanding grip force control in tasks that might produce fatigue, like repetitive manual tasks.

Methods

Subjects

Eight right-handed females (mean age 47 ± 8 years) diagnosed with CTS (Table 1) by an experienced hand surgeon participated in this investigation. The patients recruited for this study were required to have experienced at least two of the following primary CTS symptoms when questioned during clinical examination: (1) pain and paresthesia within the distribution of the median nerve; (2) increases in pain and paresthesia during the night; (3) sensory symptoms in any one of their first four fingers (thumb = 1) or in any combination thereof; (4) self-perceived hand strength deficits; and (5) a positive Tinel’s or Phalen’s sign (Wilder Smith, Chan, & Kannan, 2007).

Tinel’s test is usually performed by tapping the median nerve over its course in the wrist. The test is deemed positive when either a tingling sensation or discomfort in the fingers is reported by the subject. With the Phalen’s test, subjects are asked to hold their wrists maximally flexed for 30–60 s. This position narrows the carpal canal and produces pressure on the median nerve. Development of paresthesia in the median nerve distribution indicates a positive sign (Sternbach, 1999). In addition, symptoms were required to have been present for at least 6 months before their participation in the study (Fernandez-de-Las-Penas, Perez-de-Heredia-Torres, Martinez-Piedrola, de la Llave-Rincon, & Cleland, 2009; Wilder Smith et al., 2007).

Eight healthy females also were recruited as controls, matched both for age (±2 years) and hand laterality (right vs. left hand affected). To be eligible as a control, an individual could have no history of any upper limb disorder or any other condition that could affect their physical performance during the experimental tasks. For both groups, exclusion criteria were: (1) deformities in the upper-limb; (2) a history of upper-limb trauma within the six months preceding their participation in this study; (3) cervical radiculopathy; (4) prior carpal tunnel release surgery; (5) pregnancy; and (6) being treated for arthritis, neurologic disease, chronic alcoholism, diabetes, hypothyroidism, gout, or fibromyalgia. All participants signed an informed consent form approved by the local Ethics Committee. By self-report, all were right hand dominant.

Clinical Evaluation

Before the assessment of grip force control, the following clinical tests were performed:

(1) Semmes–Weinstein monofilaments (Touch-Test Sensory Evaluators, North Coast Medical Inc., USA) were used to evaluate the tested hand’s mechanical
Table 1  Characteristics of the Individuals With CTS

<table>
<thead>
<tr>
<th>No.</th>
<th>Age (years)</th>
<th>Evaluated hand</th>
<th>Time since diagnosis (years)</th>
<th>Clinical Tests</th>
<th>BCTQ</th>
<th>SWT (Threshold)</th>
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<td>Left</td>
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</table>

Mean ± SD 47.13 ± 7.83

BTQ, Boston Carpal Tunnel Questionnaire; SYMP-score, symptom severity score; FUNCT-score, functional status score; SWT, Semmes–Weinstein monofilament test; SD, standard deviation.
sensory threshold (MST). For this evaluation, the following monofilaments (and their corresponding pressures) were used: 2.83 (4.86 g/mm²), 3.61 (17.7 g/mm²), 4.31 (33.1 g/mm²), and 6.65 (439 g/mm²), where 2.83 corresponds to a normal sensory threshold and 6.65 to an abnormally high threshold.

(2) Boston Carpal Tunnel Questionnaire (BCTQ), which includes both a symptom severity scale (SYMP-score) and a functional status scale (FUNCT-score). Each of these scales generates a final score (the sum of individual scores divided by the number of items) which ranges from 1 to 5, with higher scores indicating greater disease severity. The BCTQ has been used as an outcome measure in clinical studies, and has undergone extensive testing for validity, reliability and responsiveness (Levine, et al., 1993).

(3) Dynamometry to evaluate maximal voluntary contraction (MVC) while gripping.

Assessing Grip Force

**Apparatus** A hand-held digital dynamometer (20 cm in length, 19 cm in height and weighing 700 g) was used to assess maximal voluntary grip force and to induce fatigue in the subject’s hand. The handle of the device consists of two parallel cylindrical bars (a lower bar 17 cm in length and 2.0 cm in diameter, and an upper bar 14 cm in length and 1.7 cm in diameter). Each subject was instructed to place her thumb on the lower bar and her other four fingers on the opposite bar of the dynamometer. The distance between the two bars was adjustable from 38 to 140 mm to suit any hand size. Four strain gauges (Kyowa Electronic Instruments, Japan) in a complete Wheatstone Bridge Circuit, measured the grip force applied by the sum of individual fingers to the dynamometer handle. The output signal was amplified and directed to an A/D converter sampled at a rate of 100 Hz. Software in C++ language acquired and recorded the data.

To test grip force control, each subject manipulated a cylindrical plastic object (6 cm in diameter, 16 cm in height, and weighing 431 g) fitted with a piezoelectric force sensor (model 208CO3; PCB Piezotronics Inc., Depew, NY, USA) placed at the object’s center (Figure 1A). Two metallic projections connected the force sensor to two aluminum pads on the external surface of the object (grasping surface). A three-axial piezoelectric accelerometer (model 333B32; PCB Piezotronics Inc., Depew, NY, USA) was fixed to the cylindrical object to register acceleration in the X, Y and Z planes. Before data collection, accelerometer and force sensor signals passed through two signal conditioners (ICP R Sensor Signal Conditioner, Model Y482A22 and Line-Powered (AC) ICP R Signal Conditioner, Model 484B06, respectively, PCB Piezotronics Inc., Depew, NY, USA). The signals were collected via a customized program in LabView Signal Express (Version 2.5.1 for Windows, National Instruments, Texas, TX, USA) and sampled at 100 Hz with a 16-bit A/D converter (model PCI 6220, National Instruments, Texas, TX, USA).

Experimental Procedures

Before each experiment, subjects washed their hands, after which alcohol swabs were used to further clean the individuals’ fingers and the metallic surfaces of the object. The participants were positioned in an adjustable chair in front of a table,
with their trunk upright and feet flat on the floor. The shoulder of the experimental hand was flexed to approximately 30°, with the elbow in approximately 90° of flexion, the wrist in a neutral position and the forearm in a midprone position. Subjects grasped the object by the aluminum pads using their thumb and four opposing fingers (Figure 1B). They were instructed to perform all the trials with the same cadence, which was to be as “natural” as possible. They were not allowed to tilt the object or move their trunk during object manipulation. Each individual performed two practice trials before data were collected.

Five consecutive trials of grasping and lifting the test object were performed by each subject before and following a fatigue protocol (described below). Each trial consisted of lifting the object vertically to a height of approximately 10 cm above the table, holding it there for 5 s, and then placing the object back on the table after receiving the experimenter’s command.

Trials to measure slip force were performed between the vertical lifting trials without and with hand fatigue. To assess slip force, each subject performed five vertical lifting trials that consisted of lifting the object, holding it over the table, and then slowly decreasing their grip until the object slipped out from between their fingers and thumb. Trials in which subjects failed to accomplish the assigned task were discarded. The slip force of the five trials was inspected visually on a computer screen and the mean value of the three best trials (in terms of clearer sharp acceleration deflection) was calculated and used for further analysis (Blennerhassett et al., 2006).

**Fatigue Protocol**

Before the fatigue protocol, the maximal voluntary contraction (MVC) associated with each subject’s grip force was determined using the digital hand-held dynamometer. The subjects were instructed to hold the device with their thumb and four opposing fingers (power grip), and then to squeeze it with as much force as possible
for 6 s. Three trials were performed, with a time interval of 180 s between each trial pair. The highest value attained across these 3 trials was selected as grip force MVC.

The fatigue protocol involved several trials of isometric force production with visual feedback. Each trial consisted of having the subject reach 50% of her MVC value and maintaining it for 30 s. Subjects were instructed to track their force production on a computer screen to help them to maintain the required level. The computer software presented horizontal bars on the screen to facilitate visualization of the individual’s force production. The trials were repeated, with a time interval of 10 s between successive trials, as many times as necessary to produce fatigue. The hand was deemed ‘fatigued’ when the subject could no longer achieve 25% of their MVC and maintain it over the first 20 s of the trial (Figure 2). The subject’s MVC was assessed immediately after the fatigue protocol and again following the last trial of the functional tasks (object manipulation).

**Data Processing**

The force sensor and accelerometer signals were processed using a customized Matlab program (Version 6.5, Mathworks Inc., Natick, MS, USA). Grip force and the onset of vertical acceleration were identified for each trial visually and automatically through an algorithm in Matlab. This algorithm determined the onset times of both curves when it found, at the beginning of the curves, a point that represented 5% of the corresponding curve’s peak.

From the grip force and acceleration signals, the outcome measures were obtained as follows:

(1) Load Force Peak (N), calculated by multiplying the object’s mass (kg) by vertical (Z-axis) acceleration and gravity (g) (\(LF= m\sqrt{AccZ+g^2}\)) (Hermsdorfer, Hagl, & Nowak, 2004; Nowak et al., 2002). Loading components acting in the direction of the applied grip force (X-axis), and sagittal (Y-axis)
to it, were not included in the calculation of the object’s load force. Since the performed tasks consisted of vertical lifting trials without object tilting, these loads were minimal and required no compensation by prehensile grip force to prevent the object from slipping.

(2) Grip Force Peak (N), defined as the maximum grip force applied by the thumb and four fingers on the object during the lifting phase—that time between the point of liftoff, when the acceleration of the load force first became different than zero, and the point when acceleration returned to approximately zero (Johansson & Westling, 1984).

(3) Safety Margin (N), measured as the difference between the static force and slip force (Blennerhassett et al., 2006; Iyengar, Santos, & Aruin, 2009). This variable is the result of grip force adaptation to the obtained object properties via actual sensory feedback information (Nowak & Hermsdorfer, 2003b). Static force was defined as the mean grip force during the 4 s when subjects held the object statically; i.e., the point at which movement velocity again became approximately zero after vertical lifting of the object; the last second of the task was removed to ensure that all subjects were still in a static phase. Slip force (N) was determined as the grip force measured at the time of a sharp deflection in acceleration, when the object slipped through the subject’s fingers (Blennerhassett et al., 2006; Nowak & Hermsdörfer, 2003a).

(4) Time to Grip Force Peak (in ms), defined as the time between Grip Force Onset and Grip Force Peak during the lifting phase. This measure reflects the effectiveness of sensorimotor processing while lifting an object (Fellows, Noth, & Schwarz, 1998).

Statistical Analysis

The dependent variables analyzed were Maximal Voluntary Contraction (MVC), Load Force Peak, Grip Force Peak, Safety Margin, and Time to Grip Force Peak. Two-way mixed-model analysis of variance (ANOVA) was performed with a between-subjects factor of ‘group’ (CTS vs. controls) and a within-subjects factor of ‘fatigue’ (before vs. after fatigue). For MVC analysis, another level was added to the fatigue factor (MVC after the lifting task). Student’s t tests were used to identify post hoc effects and to assess for slip force differences between groups. To estimate slip force reliability, we computed the coefficient of variation within trials for each individual. A p value less than 0.05 was considered statistically significant, and all tests were two-tailed.

Results

Maximal Voluntary Contraction

On ANOVA, a statistically-significant group effect on MVC was identified ($F_{2,14} = 4.700, p = .048$). The mean ($\pm SD$) MVC across fatigue conditions was lower in individuals with CTS than in controls (182.23 $\pm$ 89.06 N and 260.04 $\pm$ 85.66 N, respectively). In addition, there was a main effect of fatigue on MVC ($F_{2,14} = 30.128, p = .0001$). The fatigue protocol resulted in a decrease of about 38% in MVC for both groups (Table 2); this reduction in MVC was maintained after all
No interaction between group and fatigue was found ($F_{2,14} = 0.910, p = .384$).

**Grip Force Control**

Figure 3 illustrates the curve patterns for load and grip force during the vertical lifting and static holding tasks before (left panel) and after fatigue (right panel) for one control subject and one patient with CTS (Figures 3A and 3B, respectively). Note that the force curves pertaining to lifting and holding the test object are different between these two subjects. With the control subject, a pronounced Grip Force Peak is observed during the lifting phase. This Grip Force Peak occurs during the acceleration phase of lifting (when the load force is increasing after object lift off). However, when the object is held statically, the control subject tends to decrease her grip force. Conversely, the individual with CTS exhibited a grip force that was higher during

![Figure 3](image_url)
the deceleration phase of lifting than amid the period of acceleration. Moreover, even though both individuals decreased their grip force when fatigued, the individual with CTS still applied excessive grip force during the static phase of lifting.

**Load Force Peak**

There was no effect of group (F\(_{1,7} = 2.014, p = .178\)) or fatigue (F\(_{1,7} = 0.358, p = .559\)) on Load Force Peak. In those with CTS, the mean ± SD of the Load Force Peak was 4.89 ± 0.10 N before fatigue and 4.92 ± 0.18 N after fatigue. In controls, the mean ± SD of Load Force Peak was 5.123 ± 0.33 N and 5.17 ± 0.30 N before and after fatigue, respectively. No interaction was apparent between the factors ‘group’ and ‘fatigue’ (F\(_{1,7} = 0.004, p = .948\)).

**Grip Force Peak**

Figure 4A shows the mean (± SE) value for Grip Force Peak during task performance for those with CTS and controls, before and after the fatigue protocol. ANOVA revealed a significant effect of fatigue on Grip Force Peak (F\(_{1,7} = 7.406, p = .017\)), which decreased with fatigue. No statistically-significant difference in Grip Force Peak was observed between the two subject groups (F\(_{1,7} = 27.332, p = .127\)). In addition, there was no significant interaction between group and fatigue (F\(_{1,7} = 0.008, p = .931\)).

**Safety Margin**

Figure 4B illustrates the mean (± SE) value for Safety Margin during the vertical lifting trials, before and after the fatigue protocol for individuals with CTS and

![Figure 4](image-url)

*Figure 4* — Means and standard errors of the A) Grip Force Peak and the B) Safety Margin during vertical lifting trials before and after the fatigue protocol, for controls and individuals with carpal tunnel syndrome (CTS). ** and * denote statistically-significant differences (p < .05) between groups and conditions (before vs. after fatigue), respectively.
controls. The mean ± SD of the slip forces used to calculate the Safety Margin were 2.24 ± 0.83 N and 2.13 ± 1.33 N for those with CTS and controls, respectively. No intergroup differences in slip force were identified (t14 = 0.631, p = .538). The coefficient of variation for slip force within trials for each subject in both groups ranged from 0.04 to 0.38, which represents small variability within trials. This is a strong indication that the procedure adopted to measure slip force was performed well by all subjects and consistently within trials.

The Safety Margin was significantly different between the two test groups (F1,7 = 8.909, p = .010). Those with CTS exhibited a greater Safety Margin than controls while holding the test object in a static position. After fatigue, the Safety Margin decreased significantly in both groups (F1,7 = 21.908, p < .001; Figure 4B). No significant interaction between group and fatigue was observed for Safety Margin (F1,7 = 1.299, p = .274).

Time to Grip Force Peak

Figure 5 shows mean values (± SE) for Time to Grip Force Peak before and after the fatigue protocol, for both subject groups. A statistically-significant intergroup difference was identified before and after fatigue (F1,7 = 5.024, p = .042). There was no significant effect of ‘fatigue’ on Time to Grip Force Peak, (F 1,7 = 0.224, p = .643). Similarly, no statistically-significant interaction between group and fatigue was found for Time to Grip Force Peak (F1,7 = 0.058, p = .813).

Discussion

The present investigation examined grip force control in individuals with CTS during object manipulation in the absence and presence of fatigue affecting the person’s hand and forearm muscles. We asked subjects to perform the task of lifting an object vertically and holding it statically for a few seconds. Individuals with
CTS gripped the object more tightly and took longer to achieve their maximum grip than healthy matched controls. The effect of fatigue was that it lessened the grip in both groups.

**Group Comparison**

Those with CTS applied unnecessarily elevated grip force during the static phase of their task, both before and after the onset of fatigue. One possible explanation for this outcome is that they had decreased sensory information from their fingertips; in other words, they had to grip more tightly to feel the object to a degree that made them comfortable. Such decreased sensation is common among individuals with CTS (Jackson & Clifford, 1989; Radwin et al., 1991), and this was confirmed in our subjects via the results of Semmes–Weinstein monofilament testing. The effects of sensory deficits in the fingertips on grip force control have been investigated in several other studies. Unnecessarily high grip force has been observed in patients with a variety of disorders affecting sensory function, including multiple sclerosis (Iyengar, Santos, Ko, & Aruin, 2009), basal ganglia disorders (Serrien, Burgunder, & Wiesendanger, 2001; Serrien, Li, Steyvers, Debaere, & Swinnen, 2001), and stroke (Hermsdorfer, Hagl, Nowak, & Marquardt, 2003). For instance, Nowak and Hermsdörfer (2003b) observed greater grip force in patients with tactile sensory impairment than in controls, and this averaged 30–50% higher during the dynamic and static phases of the assigned task. Based upon the results of the current study, CTS should be included among those disorders that cause patients to hold objects with unnecessarily elevated grip force.

Previous studies on grip force control in individuals with CTS have demonstrated similar results regarding increased grip force. For instance, Lowe & Freivalds (1999) investigated grip force control in CTS patients performing a task that simulated hand tool use in the workplace. The individuals were required to grasp a hand tool device (tool/stylus) using a precision pinch, and then to apply a force on a rigid tracking surface to match a target force. This target force was represented by sine waves displayed on an oscilloscope to control the frequency and magnitude of the application force. The ratio between the grip and applied forces (or reactive force) over the duration of the sinusoid function was calculated (Lowe & Freivalds, 1999). Those with CTS exerted higher pinch forces at equivalent levels of application force than healthy controls. In the current study, subjects were asked to perform the common task of lifting an object vertically off a table, and the reactive force was not calculated; however, the increased safety margin demonstrated in individuals with CTS is a similar result. Thus, individuals with CTS are likely to use greater grip force even when performing tasks in which a precise grip is required, as well as during common daily functional tasks like holding an object. Such increased grip force might exacerbate whatever inflammatory process exists within the carpal tunnel, further increasing compression on the medial nerve and, in turn, aggravating the CTS symptoms of pain, paresthesia, weakness, and clumsiness of the hand and fingers, all common complaints among patients with CTS (Agabegi, Freiberg, Plunkett, & Stern, 2007a).

In our study, individuals with CTS took significantly longer to maximize their grip while lifting an object. The parameter we used to measure this—Time Grip Force Peak—is considered an important indicator of motor control during
sensorimotor processing (Fellows et al., 1998). Stroke and Parkinson’s disease patients also are slower to achieve peak grip force due to a decreased Grip Force Peak Rate (Fellows et al., 1998). This latter variable was not evaluated in the preset study; however, it is possible that the Time to Grip Force Peak was increased in individuals with CTS because they kept increasing their grip force during the deceleration phase of lifting, and not just during acceleration, as controls did. This difficulty regulating grip force observed temporally in our CTS subjects may reflect the motor and sensory deficits in the hand caused by peripheral nerve entrapment. Somatosensory deficits might particularly deprive the CNS of accurate information regarding a manipulated object’s innate physical characteristics and movement, rendering these individuals incapable of effectively regulating changes in the magnitude of their grip.

The Effects of Fatigue

The fatigue protocol that we used was successful at inducing muscle fatigue that persisted until each subject’s assigned tasks were completed. Overall, subjects experienced a reduction of almost 40% in their maximal force, which is close to the reduction obtained by other fatigue protocols used in previously-reported studies (Corcos, Jiang, Wilding, & Gottlieb, 2002; Danion et al., 2001; Kanekar, Santos, & Aruin, 2008).

The main fatigue-induced change in grip force control that we observed in this study was decreased grip force when the test object was grasped and lifted. Such decreased grip force was manifested in both groups as both a reduced Grip Force Peak and Safety Margin.

It is important to highlight that, even though those with CTS and controls were able to generate appreciable grip force despite muscle fatigue (of approximately 150–200 N), they nonetheless decreased the strength of grip they could muster to lift the test object, which required approximately 5 N to be lifted (disregarding the object’s friction properties). Therefore, the decrease in grip force after fatigue could indicate a central strategy to maintain grasping stability while experiencing a deficit in peripheral force.

Previous investigators have shown that the effect of peripheral fatigue is not limited just to changes in the force-generating capabilities of muscles, but has a significant central neural component as well (Corcos et al., 2002; Danion et al., 2001; Kanekar et al., 2008). It has been demonstrated that, after fatigue, individuals change their neural control (muscular activation pattern) or coordination strategy, or both, to retain the major features of the task (Gates & Dingwell, 2008). For example, Corcos et al. (2002) reported that, when the muscular torque and speed of elbow flexion decreases following fatigue of elbow flexors, the temporal pattern of muscle activation is changed to preserve movement accuracy. Thus, in the current study, individuals decreased their grip force but still were able to complete their tasks. Such a diminution in grip force might be economically viable from an energy point of view; but, at the same time, it might increase the risk of a hand-held object slipping from one’s grasp. Individuals with CTS, in particular, appear to decrease their grip force when fatigued; however, they still maintain force levels similar to those of controls before fatigue. This might represent a form of compensation to prevent objects from slipping from their hand during their daily manual activities,
since the sensation of fatigue is a common complaint among individuals with CTS (Schenker et al., 2006).

Despite the relatively small number of participants in our study, we identified significant differences in most variables (Grip Force Peak, Safety Margin, and Time to Grip Force Peak), either between groups or between fatigue conditions. It is unlikely, therefore, that hitherto identified significant differences in grip force control would disappear with a larger pool of participants. However, further research with a larger sample is warranted to investigate the control of grip force in patients in different stages of CTS (or with different levels of sensory threshold).

**Conclusions**

In our study, individuals with CTS performed a functional lifting and holding task via an increased Safety Margin and prolonged Time to Grip Force Peak, both before and after fatigue. This underlines the influence of motor and somatosensory deficits on the regulation of grip force caused by median nerve entrapment. In the presence of fatigue, our subjects with and without CTS decreased their grip force, which might increase the likelihood of accidental slips. Such changes may reflect the role of a central strategy during peripheral fatigue. The outcome of this study provides a better understanding of grip force control when muscles are fatigued. This should be considered when designing therapeutic strategies to enhance hand function in patients with peripheral nerve diseases like CTS.

**References**


