Chapter 3

Quantification of Behavioral Consequences of Carpal Tunnel Syndrome: Insights from Biomechanical Analysis of Grasping and Manipulation

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Abstract

Carpal Tunnel Syndrome (CTS) is known to affect manual dexterity. Electrodiagnostic tests are often used to quantify the extent of damage (mild to severe) of the median nerve. However, these clinical measures of median nerve damage cannot be used to quantify the extent of hand functional deficits. To address this question, several recent studies have been conducted to quantify the behavioral effects of CTS on patients'

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ability to perform grasping and dexterous manipulation. These studies have used biomechanical analyses to identify functional deficits in hand control due to sub-optimal sensorimotor integration caused by reduced tactile sensitivity at a subset of the digits. We review published studies and present novel findings about the effects of CTS on patients' sensorimotor deficits. These deficits are revealed by tasks that require the ability to integrate sensory feedback with motor commands for coordinating digit forces and position. The findings of this research have shown that chronic median nerve compression affects the ability to coordinate preprogrammed and feedback-driven control for effective and efficient force adaptation in multi-digit grasping.

Introduction

The hand is essential to human motor behavior and is one of the most studied and complex motor systems. Its elaborate biomechanical and neural architecture underlies its ability to assume a uniquely rich repertoire of postures that can mold and exert forces onto virtually any object, enabling us to perform an incredible range of manipulatory behaviors. For successful object manipulation, somatosensory feedback (from tactile, joint and muscle receptors) about object properties must be integrated with motor commands, i.e., sensorimotor integration. For example, when lifting a glass, properties such as center of mass, weight, and texture need to be accurately sensed by the hand to select an appropriate distribution of digit forces such that the glass neither slips or tilts, nor crushes. Effective control of digit forces relies on both anticipatory and feedback-driven control mechanisms, each of which requires sensorimotor integration.

The ability to anticipate object properties is based on acquiring, storing and retrieving memories associated with previous manipulations of a given object (Gordon et al., 1993, Jenmalm et al., 1997; Johansson, 1998; Johansson and Westling, 1984, 1987, 1988a, b; Salimi et al., 2000, 2003). This mechanism is used to plan and execute – in an anticipatory fashion – the forces necessary to manipulate an object without having to rely on sensing object properties that would occur during object manipulation, e.g., before the object is lifted (Fu et al., 2010; Zhang et al., 2010). Feedback mechanisms are known to play a crucial role in upgrading erroneously planned fingertip forces (Augurelle et al., 2003; Johansson, 1996, 1998; Macefield, 1996; Monzee et al., 2003; for review see Johansson and Flanagan 2009). In healthy subjects, the coordination of digit forces has been extensively studied across the

different phases of grasping, e.g., force rise (i.e., from contact with the object to onset of object manipulation), object manipulation (i.e., lift), static hold, or dynamic transport of the object, and object release (Forssberg et al., 1991, 1992; Rearick et al., 2002, 2003; Rearick and Santello, 2002; Reilmann et al., 2001; Santello and Soechting, 2000; Smith and Soechting, 2005). The force rise phase is important to assess anticipatory force mechanisms, whereas lift and hold phases are important to detect changes in digit force coordination that might be elicited by feedback mechanisms.

Studies in healthy individuals have suggested that visual and somatosensory feedback need to be processed and integrated with motor commands such as to initiate the complex spatial and temporal coordination of the digits required for skilled manipulatory behaviors (Gordon et al., 1993; Jenmalm and Johansson, 1997; Jenmalm et al., 2000; Johansson and Cole, 1994; Salimi et al., 2003). However, the delicate multi-digit force coordination that can be flexibly adapted to object properties (such as size, friction and weight) can be disrupted by a number of neurological and musculoskeletal diseases, such as Carpal Tunnel Syndrome (CTS). CTS is a compression neuropathy of the median nerve resulting in 1) somatosensory deficits in the thumb, index, middle and lateral half of the ring finger, and, in severe cases, 2) motor deficits in the thumb. Prolonged mechanical compression of the nerve can result in ischemic damage and/or changes in the myelination of the nerve, which in turn leads to slowing of axonal conduction velocity, nerve block, and in severe cases axonal loss (Nora et al., 2004; Welford, 1972). Patients with CTS suffer from a constellation of symptoms including aching and burning, tingling, numbness, weakness and clumsiness in the affected hand. In addition, CTS is one of the most common neuromuscular diseases affecting hand function and therefore dexterous manual tasks performed during activities of daily living. Physicians often hear complains such as 'easily dropping objects', or 'having problems with buttoning the shirt' from patients who have been diagnosed as CTS. It affects 6 to 14 million adults in the United States and there is a 10% lifetime risk of developing the syndrome. Complications from CTS result in an average of 25 days lost from work per employee per year (Wing, 2006) with an average lifetime cost of $30,000 per individual in the U.S. (fact sheet by NINDS). It is estimated that 400,000 CTS surgeries are performed in the US each year (Mondelli et al. 2004). Because of the high prevalence of this disorder and its potential for disability, it is imperative that effective techniques quantifying complex aspects of grasping and manipulatory behaviors be made available to clinicians to help improve diagnosis and determine the effectiveness of clinical interventions. While the

physiological and pathological perspectives of CTS has been extensively studied and established, especially in available diagnosis methodology and treatment assessment (see review Jablecki et al., 1993; Massy-Westropp et. al., 2000; Verdugo et al., 2008), much less is known about the effect of CTS on sensorimotor integration underlying the control of grasping and manipulation.

Additionally, we start to appreciate the fundamental significance of sensorimotor integration on manipulatory behavior when the use of somatosensory information from the digits is impaired by a neuropathy or neurological disorder. Associated with somatosensory deficits in the thumb, index, middle and lateral half of the ring fingers, CTS poses unique challenges for the Central Nervous System (CNS) for whole-hand manipulation as it selectively impairs sensorimotor function at a subset of digits. This raises the question of how the CNS integrates sensory information, from CTS-affected and non-affected digits, with motor commands to fine-tune digit forces to task requirement. As such, CTS can be used as a model to provide insight into the mechanisms of mapping "noisy" somatosensory feedback into motor commands for anticipatory and reactive force control responsible for skilled object manipulation. In this, we review recent findings from our work based on biomechanical analysis of multi-digit force adaptation and coordination as a function of object properties and grip type.

CTS and Control of Object Grasping and Manipulation

It is believed that repetitive motion of the hand is a major factor of pathogenesis of cumulative trauma disorders (Kiser 1987). For example, the high prevalence of CTS is reported in occupations characterized by large and repetitive hand forces (Silverstein et al. 1987). It has been suggested that CTS maybe caused by the tendon and nerve movement during prolonged repetitive hand movement (Ugbolue et al. 2005), as well as the migration of lumbrical muscles into the carpal tunnel during fingers' active flexion movement, thus leading to increased carpal tunnel pressure (Siegel et al. 1995; Yii and Elliot 1994; Cobb et al. 1995). Driven by its high prevalence, CTS has been recognized in many recent studies in investigating biomechanical characteristics of carpal tunnel structures (Xiu et al. 2010), efficacy of conservative treatments or theoretical basis for surgical treatments in CTS patients (Li et al. 2009; Guo et al. 2009; Massy-Westropp et. al., 2000;

Verdugo et al., 2008). Despite studies that focused on the biomechanical, physiological, and pathological perspectives of CTS, there has been little research on the impact of CTS on activities of daily living. For an example, taking a sip from a glass requires a series of actions including objects' grasping and lifting while generating accurate forces and moment of force.

In a series of recent studies, we investigated the effects of CTS on sensorimotor integration revealed by the learning and adaptation of multi-digit coordination patterns during object grasping and manipulation (Zhang et al. 2011, 2012, 2013; Afifi et al. 2012).

These studies used the following protocol:

1) As one of the exclusion criteria, patients affected by severe CTS have been excluded from our studies as severe CTS affects thumb motor function. Therefore, only patients diagnosed with mild or moderate CTS severity, as well as age- and gender- matched controls, were recruited for our studies. This approach enabled us to focus on CTS-induced sensory deficits (please see Zhang et al. 2011 for a detailed description of inclusion and exclusion criteria).

2) The hand-held object to be manipulated was a customized inverted-T-shape grip device (Figure 1), attached with five six-component force/torque transducers (F/T, ATI Industrial Automation) to measure forces and moment-of-forces produced by each digit. A position/orientation sensor (P/O, Polhemus Fastrak) was positioned on the top of the object to determine the occurrence and magnitude of object roll during lift.

3) We instructed subjects 'to grasp, lift, hold (~4 s) and replace the object while keeping its vertical orientation'.

4) We systematically altered object properties to investigate multi-digit force coordination and adaptation. Our studies focused on the modulation of digit forces to object mass (Zhang et al. 2011, 2013), mass distribution (Zhang et al. 2012), and surface texture (Afifi et al. 2012). No explicit cues were given to subjects about these properties such that subjects had to sense (on a given trial) and recall (on subsequent trials) a given object property experienced on previous trial(s).
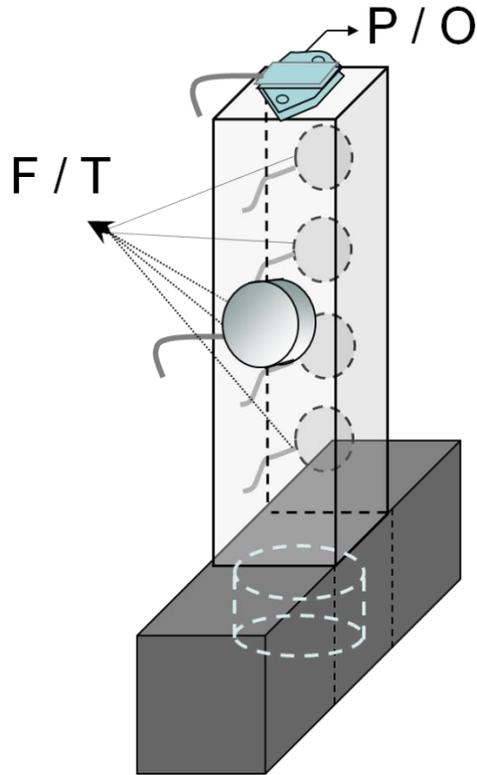
Figure 1. *Grip device used for the experiments.* Force/torque sensors (F/T) are mounted on both sides of the device to measure forces and moment of forces exerted by each digit (thumb, index, middle, ring, and little fingers: T, I, M, R, and L, respectively). A position/orientation (P/O) sensor was mounted on the top of the device to measure object kinematics. An extra mass could be inserted at the bottom of the grip device to alter experimental conditions in object weight (i.e., three weight conditions in Experiment 1: 445, 545, and 745 g; and two weight conditions in Experiment 4: light vs. heavy) or in object mass distribution (i.e., three center of mass conditions in Experiment 2: mass on the thumb, center, or finger sides; T_{CM}, C_{CM} and F_{CM}, respectively). Additionally, F/T sensors' surface could be covered with different textures when altering object texture experimental conditions (i.e., two texture conditions in Experiment 3: silk vs. sandpaper). The figure is from Wei Zhang et al. 2011 with authors' permission.

Mechanically, grasping and lifting an object while maintaining its vertical orientation (in 2-dimentional space) can be decomposed into two sub-tasks: 1) translate an object vertically against gravity; and 2) achieve equilibrium of resultant moment of force applied on the object. For the *vertical object*

translation sub-task, prevention of object slip or drop requires the total tangential forces (also referred to as "load force", which is exerted parallel to the object surface) exerted by all of the involved digits to be larger (e.g., during object lift) or equal (e.g., during object hold) to the object weight. Consequently, the total normal force (also referred to as "grip force", which is exerted orthogonal to the object surface) should be sufficiently large so that the normal-to-tangential force ratio at each digit is greater than the ratio at which slip would occur (safety margin; Westling and Johansson 1984). Additionally, the normal force exerted by the thumb and the opposing digit(s) must be equal in magnitude, and opposite in direction, to avoid horizontal translation. For the *moment equilibrium sub-task*, the resultant moments exerted on the object in the frontal plane must be equal to zero. In this scenario, moments exerted by all of the involved digits must be either equivalent to zero when lifting an object with symmetric mass distribution, or non-zero to counterbalance an external moment caused, for example, by the object's asymmetrical mass distribution. Although the above mechanical requirements constrain how digit forces must be coordinated, there are other digit force parameters that are not constrained by the task mechanics. For example, maximal grip force is not uniquely defined by the task - as long as the object is not fragile, even though there is a requirement of minimum grip force required by the need to prevent object slip. Additionally, normal force sharing patterns among individual fingers are not defined by the task, i.e., subjects can still satisfy the above-described mechanical requirements while adopting many different multi-digit force sharing patterns.

CTS and Anticipatory Grasp Control

In healthy individuals, to successfully accomplish above task requirement, visual and somatosensory feedback is processed and integrated with motor commands to control multiple digit forces (Gordon et al. 1993; Jenmalm and Johansson, 1997; Jenmalm et al. 2000; Johansson and Cole, 1994; Salimi et al. 2003). Task-specific sensorimotor memory of complex spatial and temporal coordination of the digits can be formed upon exposure to repetitive hand-object interactions, and retrieved before grasp execution on subsequent trials. Experimentally, sensorimotor learning has been examined by quantifying how multi-digit force coordination patterns are flexibly adapted to object properties such as weight (Gordon et al. 1993), mass distribution (Fu et al., 2010), and friction (Aoki et al. 2006) in an anticipatory fashion (i.e., before object lift

onset). These findings raise two questions regarding the extent to which CTS patients, affected by impaired sensation at a subset of the digits, can accurately perform grasp and manipulation: Would CTS patients be able to implement anticipatory grasp control to adapt multi-digit forces to object properties? If so, would they be able to use the same control strategies as healthy controls?

The results of our recent studies indicate that CTS patients were able to grasp, lift, hold, and replace objects as instructed. Furthermore, CTS patients could still learn to adapt multi-digit forces to different object properties as quickly as healthy controls. Specifically, after experiencing manipulation of same object for 1 to 2 trials, CTS patients started to modulate multi-digit forces as a function of object weight, mass distributions, and textures in an anticipatory fashion. This ability of CTS patients to implement anticipatory digit force control was revealed by a series of experiments (Experiments 1, 2, 3 and 4).
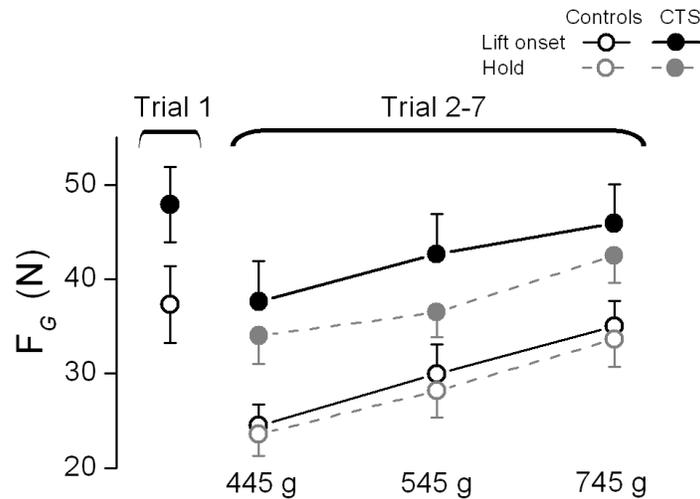

Figure 2. *Grip force at object lift onset and object hold.* Grip force (F_G) at object lift onset and during object hold on the 1st trial (averaged across all weights), and averaged across trials 2 through 7 are shown for the CTS and control groups (filled and open symbols, respectively) and each weight condition. Note that F_G during object hold on the first trial is not plotted since F_G did not change significantly across trials, i.e., F_G during hold on the first trial = F_G on trials 2-7. Vertical error bars denote standard errors. The figure is from Wei Zhang et al. 2011 with authors' permission.

In Experiment 1 (Zhang et al., 2011), both CTS and healthy controls were asked to grasp and lift an object with different weights. Note that changing object's mass affects the object vertical translation sub-task only, but not the moment equilibrium sub-task (see above). Similarly to healthy controls, CTS patients learned to scale multi-digit forces to object weight at object lift onset, as shown by larger grip force (Figure 2) and rate of grip force development for heavier objects without causing object roll. Similar CTS patients' ability of anticipatory force control to object weight was also observed in a later experiment (Experiment 4), which further revealed that CTS patients' anticipatory scaling of digit force was not affected by switching grip types requiring using a different number of digits to perform the same grasp and manipulation task (Zhang et al. 2013). In Experiment 2 (Zhang et al., 2012), object mass was the same across trials, but mass distribution was changed across blocks of consecutive trials to quantify the extent to which CTS patients could perform the moment of force sub-task. Using an object with an asymmetrical mass distribution resulted in object roll during lift on the first couple of trials. Nevertheless, object roll was minimized on subsequent trials to ~2 degrees. This is again evidence of accurate anticipatory control of a compensatory moment before the object was lifted off the table.

These findings suggest that CTS patients maintain a residual ability to process sensory feedback, form sensorimotor memories, retrieve and use them to modulate multi-digit forces prior to object lift onset. Given the sensory deficits identified by electrodiagnostic tests (details see Zhang et al. 2011), possible explanations for this residual ability to modulate digital force to object weight and mass distribution are that spared somatosensory feedback from the hand and/or that more proximal sources of feedback (such as proprioception feedback) were also utilized. Specifically, it is possible that sensory feedback from muscle, joint, and tendon mechanoreceptors in the forearm and upper arm (whose function is spared by median nerve compression) could have been integrated with residual somatosensory feedback from the hand to infer object weight and mass distribution, and coordinate digit forces after the first couple of object lifts.

Similarly, when grip surface texture was changed across blocks of trials (Experiment 3; Afifi et al. 2012), CTS patients could learn to modulate digit forces to frictional properties (slippery vs. rough) of the grasped surface. Unlike the above interpretation of the results from the studies of object mass or mass distribution, it is unlikely that spared muscle, joint, and tendon mechanoreceptors in the forearm and upper arm played a significant role in force adaptation to texture. This is because such modulation is generally

attributed to tactile mechanoreceptors in the fingertips (Birznieks et al. 2001; for review see Johansson and Flanagan 2009). We suggest the successful force adaptation to texture exhibited by CTS patients indicate the existence of spared tactile afferent fibers from the CTS-affected digits and/or the integration of afferent input acquired through the non-affected digits (i.e., little and ulnar half of the ring finger) to discriminate different textures. Additional analyses revealed that CTS patients might have increased their digit contact time to allow for tactile information to be sensed and processed given the slowing in their sensory nerve conduction.

CTS and Deficits in Sensorimotor Learning

Our findings suggest that, although CTS did not significantly affect patients' ability to perform object grasp and manipulation tasks, it interfered with the modulation of specific grasp control variables denoting CTS-induced deficits in the sensorimotor integration process. Specifically, CTS patients showed a reduced ability relative to controls to use prior experience in modulating multi-digit forces in an anticipatory fashion, i.e., at object lift onset. In fact, grip force modulation by CTS patients did not discriminate across weights and centers of mass as accurately as controls. Patients' lower discrimination was observed between light object weights in parallel with larger across-trial variability in digit force control (Experiment 1; Zhang et al., 2011), and between center and off-center mass distributions (Experiment 2; Zhang et al., 2012). Both findings underscore the importance of tactile feedback on fine regulation and reproducibility of digit force modulation to object properties.

Another deficit in anticipatory control was the CTS patients' reduced ability to balance digit forces, resulting in unnecessary net moments at object lift onset when lifting objects with a symmetrical center of mass (Zhang et al., 2011). In contrast, CTS patients learned to plan a compensatory moment to minimize object roll to the same extent as controls when lifting objects with asymmetrical mass distribution (Zhang et al., 2012). It should be noted that the discrepancy in CTS patients' difficulty in maintaining a zero moment versus their ability in anticipating a non-zero moment does not imply that CTS affects force adaptation to object mass to a greater extent than adaptation to object center of mass. As a matter of fact, in the latter scenario, multi-digit force coordination in controls fully exploited the available degrees of freedom that contribute to compensatory moment generation: modulation of digit normal

forces, tangential forces, and the location of the net center of pressure on the finger side of the device at object lift onset (Figure 3). In contrast, patients modulated *only* the finger net center pressure at object lift onset by modulating normal force sharing patterns while using the same normal and tangential forces across all object mass distribution conditions. This finding can be interpreted as solving the problem of redundant degrees of freedom by 'freezing' a subset of degrees of freedom (Bernstein, 1967; Newell, 1991; Vereijken et al. 1992). The use of this strategy might have been preferable because the modulation of one variable while keeping two other variables constant might be easier to implement than concurrent modulation of three variables as found in controls. This phenomenon might be indicative of a lower degree of flexibility of the sensorimotor system in CTS to adapt to grasp task conditions. The selective modulation of the net center of pressure also indicates that residual tactile and proprioceptive feedback in CTS can be more effectively integrated with motor commands for generating individuated finger forces than for the fine scaling of finger force magnitude. This might account for patients' reliance on exploiting finger force sharing pattern modulation to attain the desired compensatory moment.

Moreover, when the object to be manipulated was of same weight and mass distribution but different textures (Afifi et al. 2012), healthy controls tended to use a "probing" strategy prior to lifting the object by continually modulating their digit normal forces between contact and object lift-off. This suggests the healthy controls actively used sensory feedback to fine-tune their digit forces. However, this probing strategy was not evident in CTS patients, suggesting either (1) an inability to use sensory feedback to finely regulate forces, or (2) a compensatory strategy chosen by the CTS patients, i.e., the use of excessive forces, which nevertheless would preclude fine regulation of digit forces. These findings suggest that, although CTS did not affect patients' ability to perform object grasp and manipulation task, it interfered with the modulation of specific grasp control variables.

In conclusion, CTS patients exhibited deficits in sensorimotor integration as revealed by higher across-trial digit force variability, reduced ability to use prior experience to scale digit forces, lower discrimination of force modulation to lighter object weights or to center of mass, and a lower ability to minimize net moments on the object at lift onset. These findings indicate that CTS significantly affects the quality of grasp control. Therefore, we conclude that CTS does not affect macroscopic features of grasp control when adapting multi-digit forces to object properties. Nevertheless, chronic median nerve compression affects the ability to coordinate preprogrammed and feedback-

driven control for effective and efficient grip force adaptation thus denoting deficits in sensorimotor integration. The above-described behavioral deficits, although relatively subtle, result from patients' reduced ability to generate, store, and retrieve accurate sensorimotor memories of previous manipulations, thus preventing them from fully compensating for impaired somatosensory feedback. Therefore, CTS patients do not benefit from consecutive practice with object manipulation. This phenomenon leads to the inability to plan and execute manipulation as efficiently as controls.
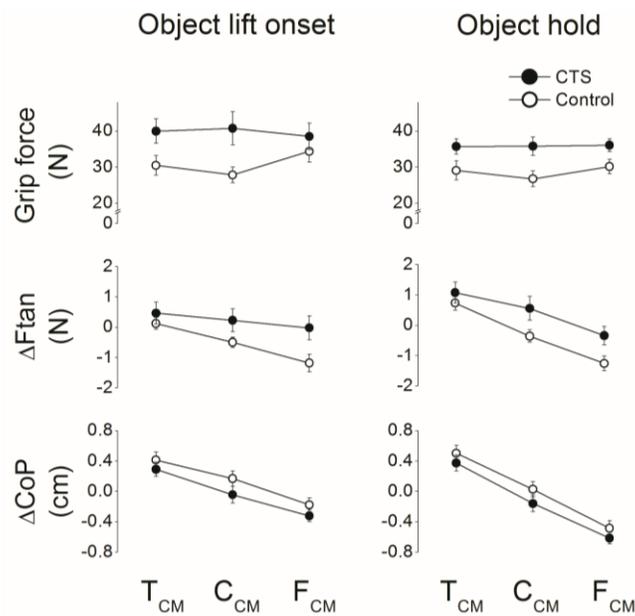

Figure 3. *Compensatory moment components*. Grip force (F_G), the difference between thumb and finger tangential forces (ΔFtan), and the vertical distance between thumb and finger center of pressure applied on each side of the grip device (ΔCoP) at object lift onset and hold (left and right column, respectively). Data are mean values averaged across trial 4 through 7 for each subject group and mass distribution condition. Vertical bars denote standard errors. The figure is from Wei Zhang et al. 2012 with authors' permission.

CTS and Excessive Grip Force

In our studies of whole-hand grasping (i.e., five digits), we have consistently found that CTS patients tend to exert significantly larger digit

normal forces than controls, irrespective of the grasping task requirement of multi-digit force modulation to object weight, mass distribution, or texture. Specifically, while exhibiting abilities to effectively scale grip force to object properties and develop multi-digit forces and compensatory moment, CTS patients' task performance was inefficient as they consistently exerted excessive forces on the object when compared to controls. This excessive force compared to controls was observed very early in the grasp on the first lifting trial, from object lift onset to object hold, and regardless of object properties, suggesting the use of a possible preprogrammed control mechanism. These observations indicate that CTS-induced sensorimotor deficits interfere with sensorimotor integration processes associated with anticipatory control mechanisms. Excessive grip force in CTS patients may represent an attempt to compensate for their sensorimotor dysfunction (slowing in sensory nerve conduction) by prioritizing effectiveness, i.e., preventing the object from slipping, over efficiency, i.e., producing just sufficient force for holding the object against gravity.

We should emphasize that CTS patients' tendency for exerting excessive grip forces does not necessarily imply a preprogrammed, 'default' strategy, as suggested by our recent CTS study on the effects of CTS on grasp control using a variable number of digits, i.e., thumb-index, thumb-index-middle, thumb-index-middle-ring, and all digits (Zhang et al. 2013). We found that the above tendency for exerting excessively large grip force in CTS patients was grip-type dependent. Specifically, CTS patients exerted excessive grip force but only for manipulations involving *both* CTS-affected and non-affected digits, i.e., thumb-index-middle-ring and thumb-index-middle-ring-little fingers (Figure 4). In contrast, patients and controls exerted similar grip force when using only CTS-affected digits. This finding is novel but counterintuitive, since patients exerted significantly larger normal forces when the more sensate digits, i.e., the ring finger, or the ring and little fingers, were added to the grasp (Figure 4). This was due to the CTS patients' producing significantly larger normal forces in the ring and little fingers than the controls, which were not sufficiently compensated for by the reduction of normal forces at the index and middle fingers. The fact that healthy controls used the same grip force across all grip types is evidence of efficient force coordination and control, and suggests that the intact CNS is not challenged by varying the number of digits in the grasp. The larger grip force exhibited by patients suggest that the effects of CTS on manipulation control are dependent on the number of digits engaged in the task, and more specifically that the combination of CTS-affected and non-affected digits leads to greater digit

force coordination deficits than grips involving CTS-affected digits only. It is therefore conceivable that the process of integrating intact and reduced sensory feedback from the fingertips might be more challenging to CNS than integrating feedback from CTS-affected digits only. While our interpretation requires further investigation, experimental evidence suggests that chronic CTS results in changes within the somatosensory system that has the potential to affect the activity of the ulnar nerve-innervated ring and little fingers. Specifically, Tinazzi et al. (1998) observed increased sensory evoked potentials in the hand somatosensory cortex of CTS patients after stimulation of the ulnar nerve. How such changes in the sensory system with respect to ulnar nerve may affect the motor output of the ulnar nerve (i.e., ring and little finger) remains to be determined.
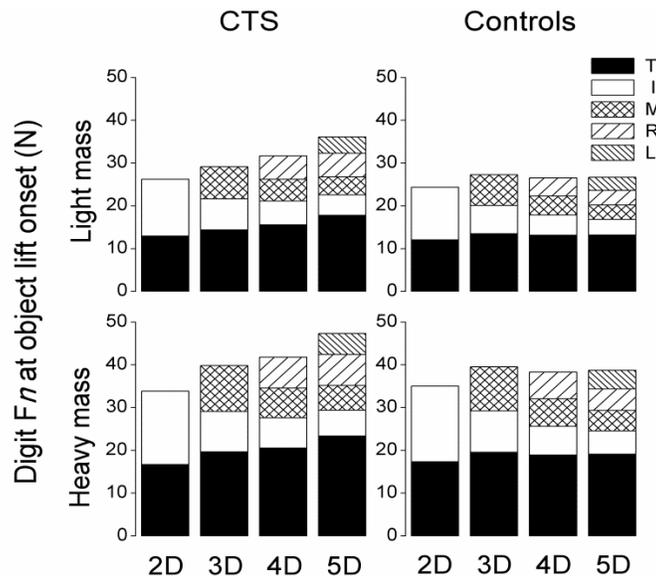

Figure 4. *Individual digit normal forces at object lift onset*. The normal force exerted by each digit at object lift onset is shown for each grip type, mass, and subject group (CTS and controls on the left and right column, respectively). Two-, three-, four- and five-digit grasps are denoted by 2D (Thumb-Index), 3D (Thumb-Index-Middle), 4D (Thumb-Index-Middle-Ring), and 5D (Thumb-Index-Middle-Ring-Little) respectively. Data are mean values averaged across trials 3 through 7 for each subject group. The figure is from Wei Zhang et al. 2013 with authors' permission.

CTS and Online Feedback Control

As described above, multi-digit force coordination quantified at object lift onset was used to examine anticipatory control mechanism responsible to object properties based on previous manipulations. Consequently, to evaluate subjects' ability of motor adaptation as a result of sensory feedback acquired following object lift onset, we have also quantified kinetic variables during the object hold phase. Following object lift and during object hold, sensory feedback about the manipulation (e.g., object tilt) becomes available through vision and residual somatosensory feedback, thus potentially allowing individuals to detect errors in the anticipatory control of grasp variables. Comparisons between these two temporal epochs should then allow the investigation of feedback-driven modulation of multi-digit forces.

One major finding based upon these comparisons was that healthy controls were able to anticipate grip force used to hold the object before lifting the object, whereas CTS patients further decreased grip force from object lift onset to object hold (Zhang et al., 2011). That is, unlike controls, CTS patients consistently overshot, from the second trial onwards across consecutive trials, grip force before lifting the object (Figure 2). We interpret the consistently larger grip force at object lift onset than during the static phase as a strategy learned during everyday activity to compensate for deficits in tactile feedback signaling distinct events of the manipulation, e.g., force development prior to object lift, the dynamic force modulation during object lift, and isometric force generation during object hold. In addition, CTS patients may prefer to use an extra safety margin of grip forces particularly during the dynamic phase, as evidenced by the fact that the younger CTS patients use a consistent safety margin, i.e., normal force above that necessary to hold the object across object textures, whereas healthy individuals modify their safety margin based on object texture (Experiment 3; Afifi et al., 2012). These results suggest that patients might have greater difficulty in anticipating the digit forces necessary to perform the task during the dynamic lifting phase than the static hold phase. Given the CTS patients' decreased ability to discriminate object weights and larger across-trial force variability, we propose that this systematic force overshoot at object lift onset vs. object hold represent a compensatory strategy that reflects different requirements and challenges to grasp stability associated with dynamic vs. static phases of manipulation.

Interestingly, we also found that CTS patients did not modulate tangential force to object center of mass at object lift onset, whereas they started to do so during object hold (Zhang et al. 2012) (Figure 3). As noted above, controls

fully exploited all three available degrees of freedom to generate a compensatory moment, while patients anticipatorily modulated only the finger net center pressure at object lift onset. This suggests that the proposed 'freezing of degrees of freedom' strategy used at lift-off was deliberate, as opposed to being unavoidable. Specifically, CTS patients might be particularly more conservative before the dynamic phase of the task than during the static phase as we suggested in our earlier work (Zhang et al., 2011). This is because avoidance of object slip or roll during the first 100–150 ms of object lift relies on feedforward control of the compensatory moment. Following object lift, however, the predictive component of compensatory moment control can be replaced by online feedback control. In addition to somatosensory feedback from the hand and the arm, vision of object orientation might have contributed to the modulation of tangential forces.

Classification of CTS-Induced Sensorimotor Integration Deficits

Our findings have shown that mild and moderate severity CTS does not affect patients' ability to perform object grasp and manipulation tasks, but that it interfered with the modulation of specific biomechanical variables. We therefore examined the specific biomechanical variables that could best distinguish grasp performance in CTS patients vs. controls, as a step towards identifying variables that could potentially be used to detect early signs of CTS-induced sensorimotor deficits. We addressed this question by using exploratory stepwise discriminant analysis on data collected in Experiment 2. We found two groups of variables that could correctly classify CTS patients and controls at different time epochs of our task. Specifically, before the object was lifted, tangential force exerted by index (Ftan_I) for the off-centered mass distribution conditions (mass on the finger or thumb sides) could account for 43% of the total variation explained by the statistical model while misclassifying only 4 out of 28 subjects into the wrong group (3 CTS patients and 1 control subject) (Figure 5A). While the object was held in the air, a combination of tangential and normal forces of the ring finger (mass on the thumb and finger side, respectively) as well as resultant tangential force control variable (mass on the finger side) could account for 58% total variation with totally 4 misclassified cases (2 CTS patients and 2 control subjects) (Fig. 5B). Therefore, it is the magnitude and distribution of tangential forces

occurring during the off-centered mass distribution conditions that appear to be the predominant behavioral difference in manipulation control between CTS and controls. Interestingly, both index and ring fingers are affected by CTS and have opposite mechanical actions by contributing to the production of pronation and supination moments, respectively, when manipulating our grip device due to their position relative to the thumb (Figure 1). According to the mechanical advantage principle, i.e., larger force production in the element(s) with longer lever arms in moment of force productions (Buchanan et al., 1989, Prilustsky 2000), finger normal force sharing at the index and little fingers were modulated the most to object center of mass. This phenomenon was likely due to the need of modulating the net center of pressure on the finger side of the grip device as a function of object mass distribution (Figure 3). However, normal forces by index and little fingers were not identified as discriminant variables for quantifying subjects' group membership. These results might be related to the differential sensorimotor impairment caused by CTS to intrinsic and extrinsic hand muscles, these muscles being primarily involved with tangential and normal force production, respectively.

Discriminant analysis was successful in identifying the digit force coordination features that best distinguished between the CTS patients and healthy controls. However, a larger number of patients across different grasp and manipulative tasks are needed to further define task-generalizable discriminant variables that best separate CTS patients from healthy individuals.

CTS Future Studies

Our recent series of CTS studies have provided insight into the grasp control mechanisms affected by the chronic compression median nerve neuropathy, carpel tunnel syndrome. The quantification of multi-digit kinetic control variables during dexterous manipulation tasks has improved our understanding of the crucial role of sensory feedback on sensorimotor integration processes responsible for anticipatory and reactive force control. We believe that this knowledge and a better understanding of CTS-induced deficits in grasping and manipulation can be beneficial towards prevention and/or treatment of CTS. Specifically, this work could have important implications for understanding the impact of repetitive hand activities in the

workplace on CTS symptoms, assisting clinicians in early and accurate CTS diagnostics and assessing the effectiveness of clinical interventions.
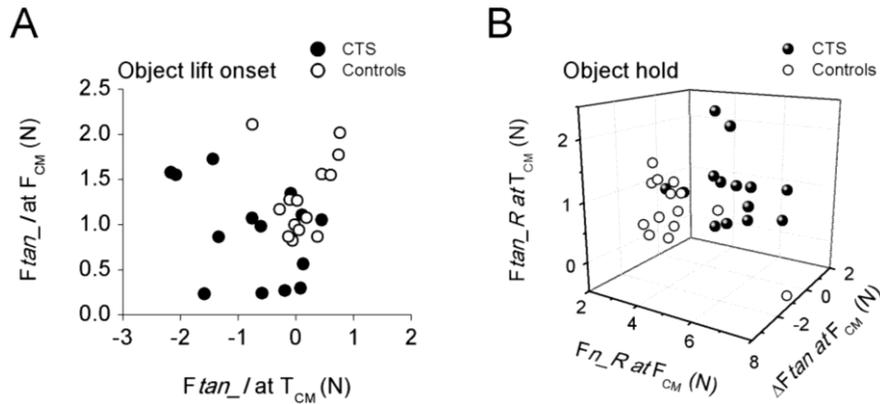

Figure 5. *Group classification based on stepwise discriminant analysis on digit forces at object lift onset and during object hold.* Statistically significant variables at object lift onset and during object hold (panels A and B, respectively) identified by stepwise discriminant analysis for differentiating CTS patients from controls. Panel A shows tangential force exerted by index finger when the mass was added on the finger or thumb side of the grip device (F_{CM} and T_{CM}, respectively) at object lift onset, whereas panel B shows tangential and normal force exerted by ring finger at T_{CM} and F_{CM}, respectively, together with the difference between thumb and finger tangential forces for the F_{CM} condition during object hold. Filled and open symbols denote data from CTS patients and controls.

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