Effects of Wrist and Fingers Postures on the Median Nerve at Proximal Carpal Tunnel

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LOH PING YEAP

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手関節および手指の姿勢が手根管の正中神経に及ぼす影響

March 2017

LOH　PING　YEAP

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List of Abbreviations

CTS	Carpal tunnel syndrome
D1	Longitudinal diameter of the median nerve
D2	Vertical diameter of the median nerve
DIPJ	Distal interphalangeal joint
FDP	Flexor digitorum profundus
FDS	Flexor digitorum superficialis
FPL	Flexor pollicis longus
IP	Interphalangeal
MCPJ	Metacarpophalangeal joint
MNCSA	Median nerve cross-sectional area
PIPJ	Proximal interphalangeal joint
TCL	Transverse carpal ligament

List of Publication

Chapter 3

Ping Yeap Loh, Hiroki Nakashima, & Satoshi Muraki. (2016). Effects of grip force on median nerve deformation at different wrist angles. *PeerJ, 4*, e2510.

Abstract

Carpal tunnel syndrome (CTS) is one of the most common work-related upper limb compression neuropathies that affects the median nerve at the carpal tunnel. Biomechanical factors such as intensive wrist-finger movements and work duration are associated with CTS prevalence. The main aim of this thesis is to improve existing prevention guidelines and ergonomics interventions on work-related CTS from the perspective of morphological changes in the median nerve. The main objectives are to investigate changes of the median nerve cross-sectional area (MNCSA) and the median nerve diameter: (1) At different finger postures and wrist angles; (2) At different grip conditions and wrist angles; (3) After continuous typing on two keyboards with different slopes.

The median nerve at the wrist was examined in six finger postures and three grip conditions, namely finger relaxation, unclenched fist, and clenched fist, with the wrist at 30° flexion, with a neutral wrist (0°), and with the wrist at 30° extension to address objectives (1) and (2). Main effects of finger postures, grip conditions, and wrist angles are significant ($p < 0.01$) in changes of the MNCSA. First, the MNCSA became

significantly smaller ($p < 0.05$) as the finger posture changed and fists were unclenched or clenched. Subsequently, wrist flexion and extension cause higher deformation of the MNCSA at different conditions. Lastly, changes of the median nerve after continuous typing tasks with 0° and 20° keyboard slopes were examined to address objective (3). Keyboard typing caused a significant increase in the MNCSA at both wrists ($p < 0.05$) in comparison to the baseline measurement. Subsequently, changes of the MNCSA when typing on keyboard of 20° slope is higher than that of 0° slope.

In summary, this thesis presented the impact of biomechanical stresses that arise from the wrist and finger postures as well as continuous keyboard typing on the median nerve in the carpal tunnel region. Following an in-depth analysis and interpretation of the results, the findings offer deeper insights into relevant factors that associate with median nerve deformation. Overall, a neutral wrist posture and less force exertion at work tasks are recommended to prevent stresses on the median nerve. Moreover, the results suggest that continuous computer work such as keyboard typing should be avoided. To conclude this thesis, general recommendations for CTS prevention and implications on current ergonomics interventions for work-related CTS are discussed.

Chapter 1　General Introduction

1.1 Carpal Tunnel Anatomy

The carpal tunnel is located within the volar wrist. Eight carpal bones form the carpal tunnel base and a tough fibrous transverse carpal ligament (TCL) forms the roof (Fig. 1.1) (Cobb, Dalley, Posteraro, & Lewis, 1993; Fess, Gettle, Philips, & Janson, 2005; Pratt, 2011). The proximal border of the TCL crosses the proximal end of the scaphoid and pisiform while the distal border of TCL is attached to the central portion of the palmar aponeurosis (Manley, Boardman, & Goitz, 2013; Pacek, Chakan, Goitz, Kaufmann, & Li, 2010; Xiu, Kim, & Li, 2010).

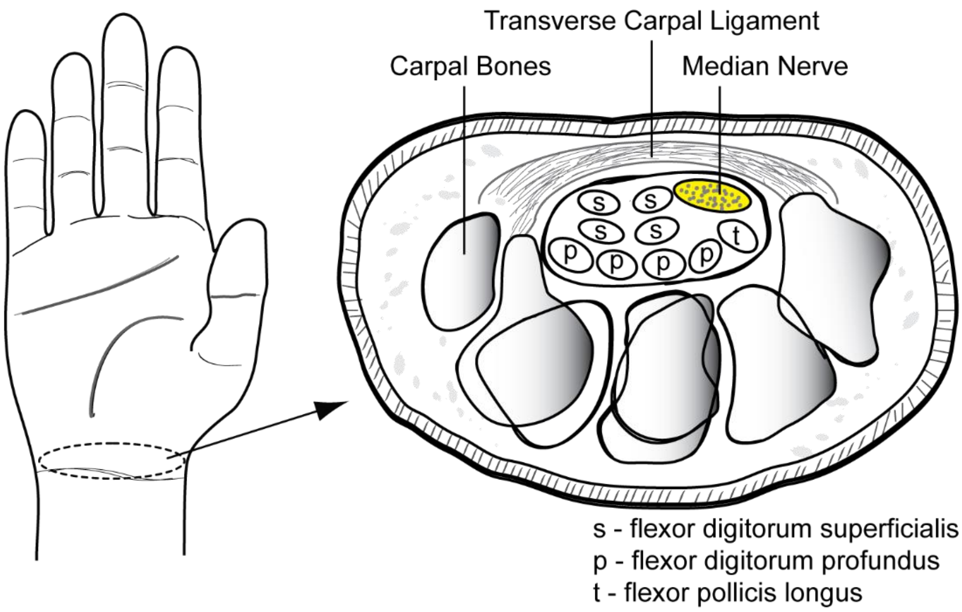

Figure 1.1 A cross-sectional view of the carpal tunnel.

Next, the carpal tunnel is tightly filled with a total of nine tendons: four flexor digitorum superficialis, four flexor digitorum profundus, flexor pollicis longus, as well as the median nerve (Pratt, 2011). Finger flexor tendons glide through the carpal tunnel during finger flexion-extension and/or wrist flexion-extension movements. The range of movements of both the finger and wrist affects the gliding amplitude of finger flexor tendons (Lopes, Lawson, Scott, & Keir, 2011; Martin, Paclet, Latash, & Zatsiorsky, 2013; Wehbé, 1987; Wehbé & Hunter, 1985). Meanwhile, kinematics of the median nerve within the carpal tunnel is affected by geometry changes of finger flexor tendons (Canuto, Oliveira, Fishbein, & Spencer, 2006; Coppieters, Hough, & Dilley, 2009; Szabo, Bay, Sharkey, & Gaut, 1994).

The shape and width of the carpal tunnel are affected by wrist postures as well as tension of the TCL (Mogk & Keir, 2007; Mogk & Keir, 2008; Mogk & Keir, 2009). The carpal tunnel volume becomes smaller with wrist flexion-extension and it leads to increases in the intra-carpal tunnel pressure, which could result in a higher compression stress to structures within the carpal tunnel (Goss & Agee, 2010; Holmes, Howarth, Callaghan, & Keir, 2011; Main, Goetz, Baer, Klocke, & Brown, 2012; Pacek et al., 2010).

1.2 Functional Anatomy of the Median Nerve

The brachial plexus is a complex network of nerves formed by spinal nerves, C5 – T1, and it supplies motor and sensory innervation to the upper extremities (Bowen, Pattany, Saraf-Lavi, & Maravilla, 2004; Franco et al., 2008; Leinberry & Wehbe, 2004). Figure 1.2 (adapted from Krotoski, 2011) shows the formation and branches of brachial plexus roots, trunks, divisions, cords, and five terminal nerves. The five terminal nerves include the musculocutaneous, axillary, radial, median, and ulnar nerve (Johnson, Vekris, Demesticha, & Soucacos, 2010; Leinberry & Wehbe, 2004).

The median nerve is formed by a combination of the medial and lateral roots (C5 – T1) of the brachial plexus and forms the median nerve at the cubital fossa level (N. Chen, Yang, & Chung, 2012; Pratt, 2011). The median nerve travels along forearm muscles and passes through the carpal tunnel to supply sensory innervation to the skin over thumb, index, middle, and radial half of the ring finger; and supply motor innervation to intrinsic hand muscles such as the lumbricals, opponens pollicis, abductor pollicis brevis, and flexor pollicis brevis (Fig. 1.3) (Leinberry & Wehbe, 2004; Pratt, 2011).

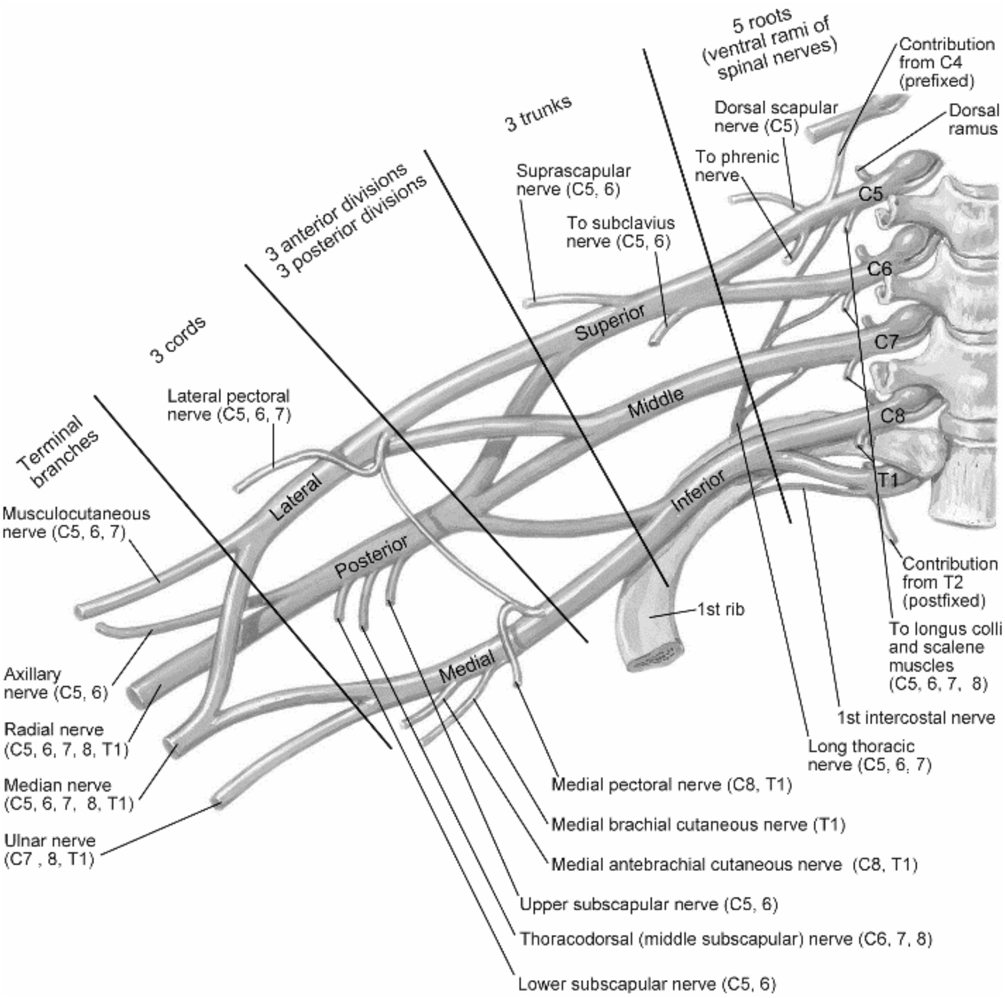

Figure 1.2 Anatomy of the brachial plexus (Krotoski, 2011).

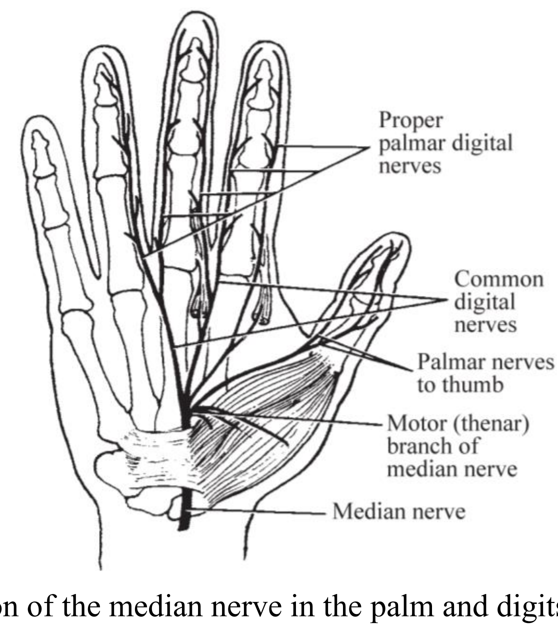

Figure 1.3 Distribution of the median nerve in the palm and digits (Fess et al., 2005).

1.3 Carpal Tunnel Syndrome (CTS)

The American Academy of Orthopedic Surgeons (AAOS) (American Academy of Orthopedic Surgeons, 2007) defines CTS as a symptomatic compression neuropathy of the median nerve at the level of the wrist with increased pressure within the carpal tunnel and decreased function of the nerve at that level. CTS is one of the most common reported peripheral nerve entrapment syndromes of the upper limb (Bland, 2007; Franklin & Friedman, 2015; Ghasemi-Rad et al., 2014; Ibrahim, Khan, Goddard, & Smitham, 2012; Lewis, Mauffrey, Newman, Lambert, & Hull, 2010).

CTS is divided into acute and chronic groups. Acute CTS could be caused by bone fractures or dislocations while chronic CTS is a more common type that is caused by multifactorial etiology (Lewis et al., 2010; Uchiyama et al., 2010). In general, the pathophysiology of chronic CTS is classified into idiopathic, mechanical factors, changes in synovial tissue, and secondary CTS (Ibrahim et al., 2012; Uchiyama et al., 2010). Several studies have suggested a theory that localized median nerve ischemia leads to the development of CTS (Kiernan, Mogyoros, & Burke, 1999; Lundborg et al., 1987; Tucci, Barbieri, & Freeland, 1997). Additionally, biomechanical stresses could elevate the intra-carpal pressure and lead to an external compression of the median nerve within the carpal tunnel level (Keir & Rempel, 2005; Uchiyama et al., 2010; Werner & Andary, 2002).

Clinical manifestation of CTS can be divided into two types: sensory and motor. Compression of the median nerve produces symptoms in the thumb, index, middle, and radial half of the ring finger. Primary sensory symptoms of CTS include tingling, pain, and numbness of the palm and fingers (Lewis et al., 2010; Zyluk & Kosovets, 2010). Subsequently, CTS motor signs such as thenar muscle atrophy could lead to a decrease in both grip and pinch strength (Viera, 2003). Both CTS signs and symptoms such as sensation and strength deficits can affect one's engagement in their daily activities, thereby affecting the quality of life (Sesto, Radwin, & Salvi, 2003).

CTS not only affects the quality of life among patients but also results in a negative impact on social and economic costs (Blanc, Faucett, Kennedy, Cisternas, & Yelin, 1996; Daniell, Fulton-Kehoe, Chiou, & Franklin, 2005; D. H. Palmer & Hanrahan, 1995). Study suggested an equal risk between men and women when exposed to similar occupation tasks (McDiarmid, Oliver, Ruser, & Gucer, 2000). However, CTS is more common in women than in men while individuals between 40 and 60 years of age are at a higher risk of bilateral CTS (Ibrahim et al., 2012; Phalen, 1966). Additionally, the prevalence of CTS in America's population is increasing up to 9.2% in women and 6% in men (Rask, 1979), with an estimated $2 billion spent on the surgical treatment for CTS each year (D. H. Palmer & Hanrahan, 1995). On the other hand, reported cases of musculoskeletal diseases and CTS in European Union countries increased to 32% while number of affected women workers increased by 39% from the years 2002 to 2005 (E. Schneider, Irastorza, & Copsey, 2010).

1.3.1 Physical Occupational Exposures and CTS

Work-related musculoskeletal disorder often leads to disabilities among workers and results in low productivity as well as high socioeconomic burden (Bureau of Labor Statistics, 2008; Daniell et al., 2005; Foley, Silverstein, & Polissar, 2007). Physical occupational exposures such forceful exertions, awkward wrist postures, repetition rate and duty cycle are identified as the main biomechanical factors that may associate with work-related musculoskeletal disorder in upper extremity. Several studies suggested that occupational and work-related biomechanical factors are highly associated with workplace CTS incidents (Bao et al., 2015; Dias, Burke, Wildin, Heras-Palou, & Bradley, 2004; Harris-Adamson et al., 2015). In addition, approximately 20% of computer users reported musculoskeletal symptoms such as muscle fatigue, painful joint, CTS, and others

(Baker, Cham, Hale, Cook, & Redfern, 2007; Sauter, Schleifer, & Knutson, 1991).

Hand-activity level (HAL) ratings, threshold limit values (ACGIH TLV©), and hand-arm vibrations (HAV) are often used to assess the relationship between risk factors of physical work exposure and CTS among manual workers (American Conference of Governmental Industrial Hygienists (ACGIH), 2000; Bao et al., 2015; Bonfiglioli et al., 2013; Harris-Adamson et al., 2015; Violante et al., 2016). On the other hand, assessments of risk factors associated with work-related musculoskeletal disorders among computer users commonly incorporate evaluation of computer workstation that is based on anthropometric characteristics, rapid upper limb assessment (RULA), rapid entire body assessment (REBA), job strain index (JSI), and others (Baker & Redfern, 2005; Hignett & McAtamney, 2000; Levanon, Lerman, Gefen, & Ratzon, 2014; Lincoln et al., 2000; Moore & Garg, 1995; Sauter et al., 1991). Nonetheless, the abovementioned methods do not provide comprehensive understanding of acute and/or chronic impact of computer work on the median nerve.

Several studies reported the kinematics of the wrist and finger during computer keyboard typing, which induces muscle fatigue and may be associated with CTS incidents among computer users (Baker, 2013; Baker et al., 2007; Rainoldi, Gazzoni, & Casale, 2008). Keyboard typing involves repetitive finger flexion-extension movements and causes deformation of the median nerve within the carpal tunnel region (Ko & Brown, 2007; Kociolek, Tat, & Keir, 2015; Lopes et al., 2011). Long-term effects of friction force on the median nerve and subsynovial connective tissue may result in soft tissue inflammation and an increase in intra-carpal pressure. However, association of computer work and CTS remains inconclusive due to insufficient epidemiology studies and limitations of study design (Andersen et al., 2003; K. T. Palmer, Harris, & Coggon, 2007; Thomsen, Hansson, Mikkelsen, & Lauritzen, 2002; Thomsen, Gerr, & Atroshi, 2008). One of the main concerns regarding pathophysiological relationship between computer keyboard typing and CTS remains questionable. Furthermore, investigation and research on the median nerve at the wrist region with special focus on work-related CTS among office workers, especially intensive computer users, are limited.

1.4 Ultrasound Imaging at the Carpal Tunnel Region

Various imaging techniques such as ultrasound, magnetic resonance imaging (MRI), and computed tomography (CT) have been used to help understand the carpal tunnel anatomy and the characteristics of the median nerve among healthy individuals and patients with CTS (Aleman et al., 2008; Duymuş et al., 2013; Ko & Brown, 2007; Mogk & Keir, 2007). MRI has demonstrated a high ability to detect pathologic changes of the median nerve as well as bowing of the TCL in patients with CTS (Jarvik et al., 2002; Jarvik, Yuen, & Kliot, 2004; Pasternack, Malmivaara, Tervahartiala, Forsberg, & Vehmas, 2003). However, MRI and CT have several limitations such as extreme room requirements for the machines, expensive costs, longer time taken for a complete scan, and contraindications for undergoing imaging.

On the other hand, high-resolution ultrasound imaging is relatively new and it is arising as a popular method for examination of the carpal tunnel. Several studies investigated morphological characteristics of the median nerve at carpal tunnel using ultrasound since the early 90s (Buchberger, Schon, Strasser, & Jungwirth, 1991; Buchberger, Judmaier, Birbamer, Lener, & Schmidauer, 1992; P. Chen, Maklad, Redwine, & Zelitt, 1997; Duncan, Sullivan, & Lomas, 1999). The quality and efficiency of high-resolution ultrasound has rapidly improved due to technological advancements in medical imaging. Over time, high-resolution ultrasound is being widely used in carpal tunnel examination to understand morphological and biomechanical characteristics of the median nerve and surrounding anatomy structures such as finger flexor tendons, subsynovial connective tissues, and blood circulation in and around the median nerve (Cartwright et al., 2008; Greening et al., 2001; Hobson-Webb, Massey, Juel, & Sanders, 2008; Hough, Moore, & Jones, 2007; Korstanje et al., 2010; Walker, Cartwright, Wiesler, & Caress, 2004; Yoshii, Villarraga et al., 2009). Advantages of high-resolution ultrasound imaging include non-invasive, dynamic and real-time imaging, portable machine size, inexpensive and easy method that can be used to investigate the behavior of the median nerve during dynamic changes of wrist and finger joints as well as to monitor acute-chronic changes of the morphological characteristics of the median nerve.

1.5 Aims and Objectives

This study is an extension of the thesis used for a previous master's degree (Loh, 2015). Effects of wrist angle changes during flexion-extension and radial-ulnar deviation on the median nerve were investigated and discussed (Loh & Muraki, 2014b; Loh, Nakashima, & Muraki, 2014). Additionally, the impact of aging on the behavior of the median nerve among older man was investigated (Loh, Nakashima, & Muraki, 2015). Wrist flexion-extension is identified as an important factor that contributes to the deformation of the median nerve within the carpal tunnel region.

In addition to the wrist posture, the finger flexor tendon gliding secondary to active finger movements results in a compressive stress on the median nerve within the confined carpal tunnel. Prior studies have investigated the displacement and deformation of the median nerve during single and multiple finger movements (van Doesburg et al., 2010; van Doesburg et al., 2012; Yoshii, Ishii, Tung, Sakai, & Amadio, 2013). Furthermore, carpal tunnel pressure is elevated when performing forceful hand exertion tasks such as gripping and pinching (McGorry et al., 2014). However, median nerve deformation under combination of wrist angle and finger movements remains unclear.

On the other hand, computer use in daily work may contribute to work-related musculoskeletal disorders such as CTS. Office workers may spend hours using computers in their daily work. However, it remains debatable whether repetitiveness and duration of computer work tasks are risk factors of work-related CTS. Wrist and finger postures when using input devices such as keyboard and mouse are likely to be the predisposing factors contributing to compression of the median nerve within the carpal tunnel. There is a lack of studies investigating changes in the median nerve's morphological characteristics after prolonged continuous keyboard typing.

The main aim of this thesis is to suggest and improve existing ergonomics intervention and prevention guidelines for work-related CTS from the perspective of morphological changes of the median nerve by ultrasound imaging. Moreover, this thesis involves research work that investigates and identifies the underlying factors that lead to median nerve changes within the carpal tunnel region such as combination of various wrist and finger postures, gripping force, and prolonged duration of keyboard typing. Therefore, the first main objective of this study is to investigate the effects of active finger flexor gliding movements and power gripping at different wrist angles on the median nerve deformation within the carpal tunnel region. The second main objective is to investigate the effects of continuous typing on median nerve changes at the carpal tunnel region at two different keyboard slopes (0° and 20°).

1.6 Organization of this Dissertation

Chapter 2 studies changes of the median nerve appearing within the proximal carpal tunnel under various finger postures at different wrist angles. The main purpose of this study is to investigate deformation of the median nerve at different finger posture known as finger tendon gliding posture at three wrist angles. Characteristics of the median nerve were measured in the cross-sectional area (MNCSA), diameter in radial-ulnar direction (D1), and diameter in dorsal-palmar direction (D2).

Chapter 3 focuses on full finger flexion and grip force exertion effects on the median nerve within the proximal carpal tunnel. The main objective of this study is to understand median nerve changes in unclenched and clenched fist positions. Furthermore, the unclenched and clenched fists were examined at three wrist angles. The median nerve at different conditions was compared to the median nerve in neutral wrist position with relaxed fingers.

Chapter 4 explores acute changes in median nerve parameters (MNCSA, D1, and D2) after typing activity. Subsequently, differences in changes of the median nerve between typing using keyboards of 0° and 20° slopes were investigated. In addition, the relationship between wrist kinematics during typing and the median nerve changes was presented for both 0° and 20° keyboard slopes.

The last chapter, Chapter 5, contains a summary of the important results and findings in this thesis. More importantly, the implications of the findings on work-related carpal tunnel syndrome are discussed. The strengths and limitations as well as directions for future study in this research area are included.

Chapter 2 Deformation of the Median Nerve at Different Finger Tendon Gliding Postures by Different Wrist Angles

2.1 Introduction

Carpal tunnel syndrome (CTS) is a compression neuropathy that affects the median nerve at the wrist region. The median nerve lies beneath the transverse carpal ligament (TCL) and is vulnerable to biomechanical stress. Various studies suggest that workplace biomechanical factors such as hand/wrist posture and hand force are associated with CTS incidents (Bao et al., 2015; Harris-Adamson et al., 2015).

Extrinsic finger flexor muscles such as flexor digitorum superficialis (FDS), flexor digitorum profundus (FDP), and flexor pollicis longus pass through the carpal tunnel and control the flexion of interphalangeal (IP) and metacarpophalangeal (MCP) joints. Active finger flexion results in the gliding of both finger flexor tendons and median nerve at different amplitudes in relation to specific finger positions, such as tabletop, hook, and full fist (Lopes et al., 2011; Wehbé, 1987). The subsynovial connective tissues enable the differential gliding between the tendons and median nerve during wrist and finger motions. However, the shear strain of the synovial connective tissue between the median nerve and tendons increases with repetitive finger motions (Tat, Kociolek, & Keir, 2013). Forceful and prolonged finger movements may lead to inflammation of the subsynovial connective tissues, resulting in higher compression stress on the median nerve and lesser nerve excursion during finger movements (Keir & Rempel, 2005).

The contributions of the extrinsic flexors and intrinsic muscles in finger joint flexion differ in each finger posture (Fig 2.1). The tendons glide distally when moving from a relaxed to straight finger position. Subsequently, the tendons glide proximally as the MCP and IP joints move into flexion position. The differential gliding amplitude of both FDS and FDP is greatest at full fist compared to straight fist, whereas the FDP glides more than FDS at the hook position (Wehbé & Hunter, 1985). Similarly, the intrinsic muscles contribute to MCP joint flexion to achieve tabletop, full fist, and straight fist along with the flexion of the interphalangeal joints. Differential tendon gliding during finger motion compresses the median nerve within the carpal tunnel. There are several studies indicating that individual or multiple finger flexor gliding causes deformation of the median nerve (Canuto et al., 2006; Ugbolue, Hsu, Goitz, & Li, 2005; Yoshii et al., 2008).

However, the carpal tunnel volume is decreased with wrist flexion and extension (Bower, Stanisz, & Keir, 2006; Mogk & Keir, 2008). Recent studies suggest that the median nerve is deformed as the wrist changes from neutral to flexion or extension among the young and the elderly (Loh et al., 2015; Loh & Muraki, 2015; Wang et al., 2014). It is known that joint movements cause elongation stress and transverse contraction of the nerve, and they result in the decrease of the nerve cross-sectional area (Millesi, Zoch, & Reihsner, 1995; Szabo et al., 1994; Topp & Boyd, 2006). Consequently, excursion of the tendons through a narrower carpal tunnel volume at wrist flexion-extension could lead to higher deformation of the median nerve. The deformation of the median nerve of different finger tendon gliding postures at different wrist angles is still remain unclear.

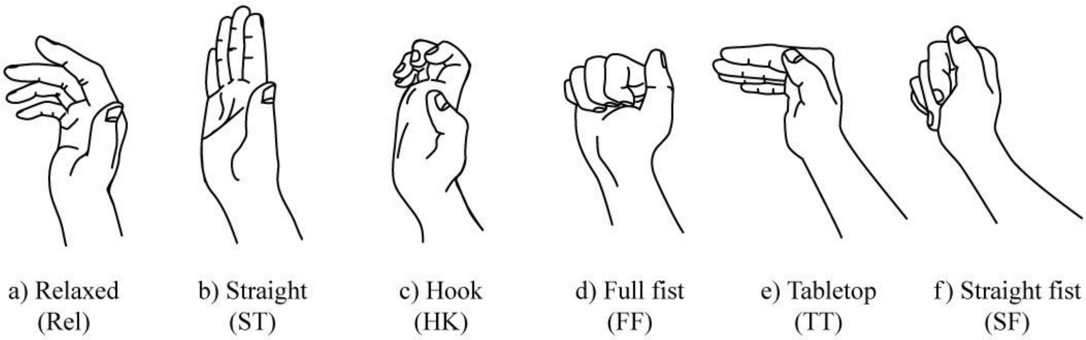

Figure 2.1 Relaxed fingers and finger tendon gliding positions.

(a) Relaxed finger;

(b) Straight finger: 0° extension of metacarpophalangeal joint (MCPJ), proximal interphalangeal joint (PIPJ) and distal interphalangeal joint (DIPJ);

(c) Hook: 0° extension of MCPJ with full flexion of PIPJ and DIPJ;

(d) Full fist: full flexion of MCPJ, PIPJ and DIPJ;

(e) Tabletop: 90° flexion of MCPJ, and 0° extension of PIPJ and DIPJ;

(f) Straight fist: full flexion of MCPJ and PIPJ, and 0° extension of DIPJ.

Therefore, the main objective of this study is to investigate the morphological changes of the median nerve, namely, median nerve cross-sectional area (MNCSA), diameter of the median nerve in the radial-ulnar direction (D1), and diameter of the median nerve in the dorsal-palmar direction (D2), of each tendon gliding finger positions at different wrist angles.

2.2 Materials and Methods

2.2.1 Participants

Twenty-five healthy male participants (Table 2.1) without known upper limb musculoskeletal pathology were recruited for this study. Informed and written consent was obtained from the participants. Edinburgh Handedness Inventory (Oldfield, 1971) was used to determine the handedness of the participants. This study was approved by the Ethics Committee of the Faculty of Design, Kyushu University (Approval number 141).

Table 2.1 Characteristics of the participants (n = 25).

	Mean ± SD
Age (years)	24.0 ± 1.8
Height (cm)	171.1 ± 4.8
Weight (kg)	64.0 ± 8.1
BMI (kg/m^2)	21.7 ± 1.7
Handedness (Right : Left hand dominant)	24 : 1

2.2.2 Ultrasound Examination Protocol

The LOGIQ e ultrasound system (GE Healthcare, USA) equipped with a 12L-RS transducer (imaging frequency bandwidth of 5–13 MHz) was used in this study. The ultrasound transducer acquisition was optimized with frequency of 12 MHz and a depth of 45 mm. A 7.0 mm thick sonar pad (Nippon BXI Inc., Tokyo, Japan) was used as a coupling agent during the ultrasound examination to minimize the compression over the wrist and to ensure a good acoustic contact between the ultrasound transducer and the skin. The examiner placed the ultrasound transducer gently on the sonar pad to minimize the pressure on the wrist throughout the examination. An L-shaped plastic frame was used to guide the angle of the ultrasound transducer during examination (Fig. 2.2). The long-arm of the L-shaped plastic frame was placed along the radius bone and the perpendicular point of the short-arm was positioned at the wrist crease (proximal carpal tunnel). The ultrasound transducer angle was maintained perpendicular to the wrist by following the short-bar of the L-shape plastic frame. The examiner placed the ultrasound transducer at the wrist crease to identify the median nerve in the transverse plane at the proximal carpal tunnel. The median nerve was identified at the superficial level by the hyper-echogenic rim containing hypo-echogenic nerve fascicles (Kele, 2012).

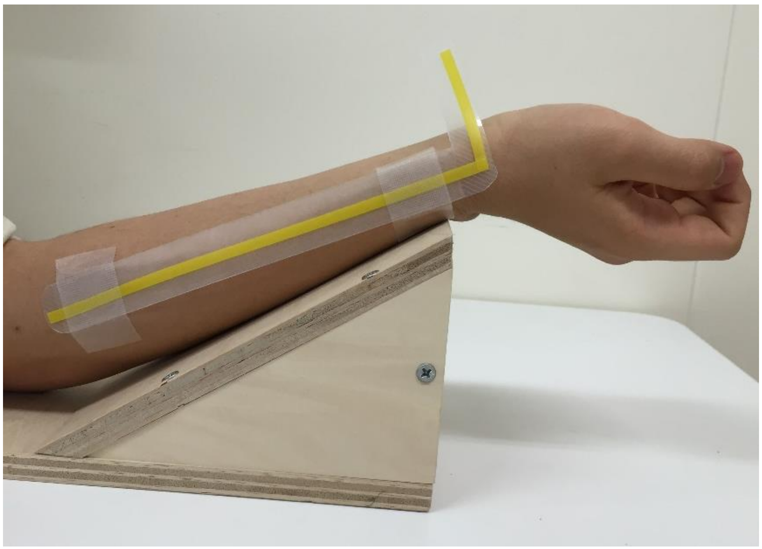

Figure 2.2 Placement of L-frame on the forearm rested on arm support.

The participants were seated with the forearm resting on an arm support on the table (Fig. 2.2). The elbow rested at 30° flexion with the forearm supinated during the ultrasound examination. Before beginning the assessment, the examiner used a 180° wrist goniometer to determine the wrist angle. First, the axis-point of the goniometer was positioned at the triquetrum. The static arm and moveable arm of the goniometer were then placed parallel to the ulnar bone and the fifth metacarpal bone to determine the wrist angle. Six finger postures were examined as follows: relaxed finger, straight finger, hook, full fist, tabletop, and straight fist (Fig. 2.1). The participants were asked to actively control and hold the wrist at designated angles (neutral 0° or 30° flexion or 30° extension) and maintain the finger posture (Fig. 2.1) with minimal effort, while three ultrasound images were taken for each finger posture. The examiner did not provide any assistance to the participant in maintaining the wrist angle during the examination process. A previous study suggests that active or passive wrist holding during ultrasound examination does not have a significant influence on the deformation of the median nerve (Loh & Muraki, 2014a). The ultrasound examination was repeated for both dominant and nondominant hands. The participants practiced maintaining the finger postures before the ultrasound examination to ensure the MCP and IP joints angle at each finger posture were held as shown in Figure 2.1.

2.2.3 Images Processing and Analysis

The recorded images were analyzed using ImageJ software (C. A. Schneider, Rasband, & Eliceiri, 2012) to quantify the MNCSA, D1, and D2 (Fig. 2.3). The median nerve was identified as a round to oval hyperechoic structure in the transverse plane across the carpal tunnel. The median nerve was confirmed by a hyperechogenic rim (epineurium) and hypoechogenic nerve fascicles. The MNCSA was measured using the tracing method (Duncan et al., 1999). First, the examiner traced the median nerve along the hyperechogenic rim. Subsequently, the Convex Hull and Interpolate functions of ImageJ software were used to adjust the outline of the median nerve to ensure the outline was fitted to the hyperechogenic rim of the median nerve. After tracing the outline of the median nerve, the longest D1 (radial-ulnar direction) and D2 (dorsal-palmar direction) were identified by two perpendicular straight lines within the outlined median nerve (Fig. 2.3). Previous study using this quantifying method showed good to excellent inter- and intra-rater reliability (Loh & Muraki, 2015). The average of three images was calculated for the MNCSA, D1, and D2 at each finger posture. The deformation percentages of the MNCSA, D1, and D2 were calculated with the following equation:

$$\text{Deformation Percentage} = \frac{\begin{array}{c}(\text{Measurement at different finger posture} - \\ \text{Measurement at relaxed finger posture at neutral wrist})\end{array}}{(\text{Measurement at relaxed finger posture at neutral wrist})} \times 100\%$$

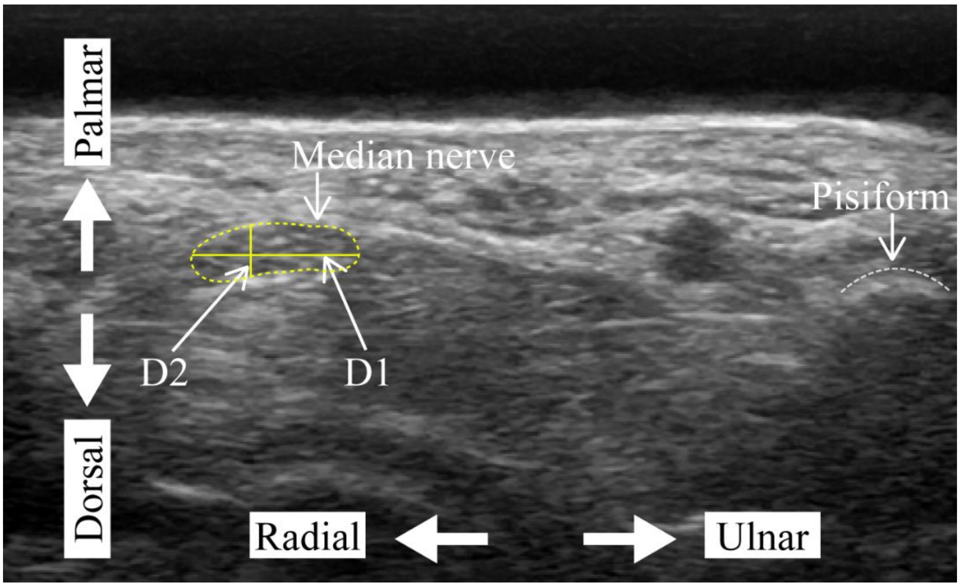

Figure 2.3 Quantification of median nerve cross-sectional area (MNCSA), and diameters of median nerve, D1 and D2.

D1, longest straight line in radial-ulnar direction; D2, longest straight line in dorsal-palmar direction.

2.2.4 Statistical Analysis

Statistical analysis was performed using SPSS version 21.0 software (IBM Corporation, Chicago, IL, USA). The sample characteristics of MNCSA in the dominant and nondominant hands were examined with the Shapiro-Wilk normality test.

Three-way repeated analysis of variance (6 × 3 × 2 factorial design) was conducted with six finger postures, three wrist angles (30° flexion, neutral (0°), and 30° extension), and handedness (dominant and nondominant) as factors to examine differences in MNCSA, D1, and D2. The post hoc pairwise Bonferroni-corrected comparison was used to examine the significant effects. Significance was set at $\alpha = 0.05$. All results are presented in mean ± standard deviation.

2.3 Results

2.3.1 Sample Characteristics

The Shapiro-Wilk test ($p > 0.05$) and visual inspection of histograms, normal Q-Q plots, and box plots indicated that the MNCSA values at the neutral wrist with relaxed finger position for both hands were approximately normally distributed and slightly skewed and kurtotic (Table 2.2) (Doane & Seward, 2011; Razali & Wah, 2011; Shapiro & Wilk, 1965).

Table 2.2 Normality test for the median nerve cross-sectional area (n = 25).

Wrist	Skewness (M ± SE)	Kurtosis (M ± SE)	Shapiro-Wilk Test (p value)
Dominant	0.28 ± 0.46	0.32 ± 0.90	0.989
Nondominant	-0.53 ± 0.46	0.10 ± 0.90	0.310

M: mean, SE: standard error

2.3.2 Effect of the Finger Posture and Wrist Angle on the Change in MNCSA

Significant interactions were found for finger posture × wrist angle × handedness ($p < 0.05$), finger posture × wrist angle ($p < 0.001$), finger posture × handedness ($p < 0.001$), and wrist angle × handedness ($p < 0.05$). Furthermore, the main effects of the finger postures ($p < 0.001$) and the wrist angles ($p < 0.001$) on the changes of MNCSA were significant. For the dominant and nondominant hands, the MNCSA at the relaxed finger was significantly larger compared to that at all other figure postures and became significantly smaller as the finger changed to other finger postures (Fig. 2.4). The MNCSA at full fist is the smallest among all finger postures. Interestingly, the MNCSA at tabletop is significantly larger than that at other finger postures. Subsequently, the MNCSA of all finger postures at neutral wrist (0°) was significantly larger compared to wrist 30° flexion and 30° extension (Table 2.3). Tables 2.3 and 2.4 summarize the mean values and the deformation percentages of the MNCSA of all finger postures at three wrist angles, respectively.

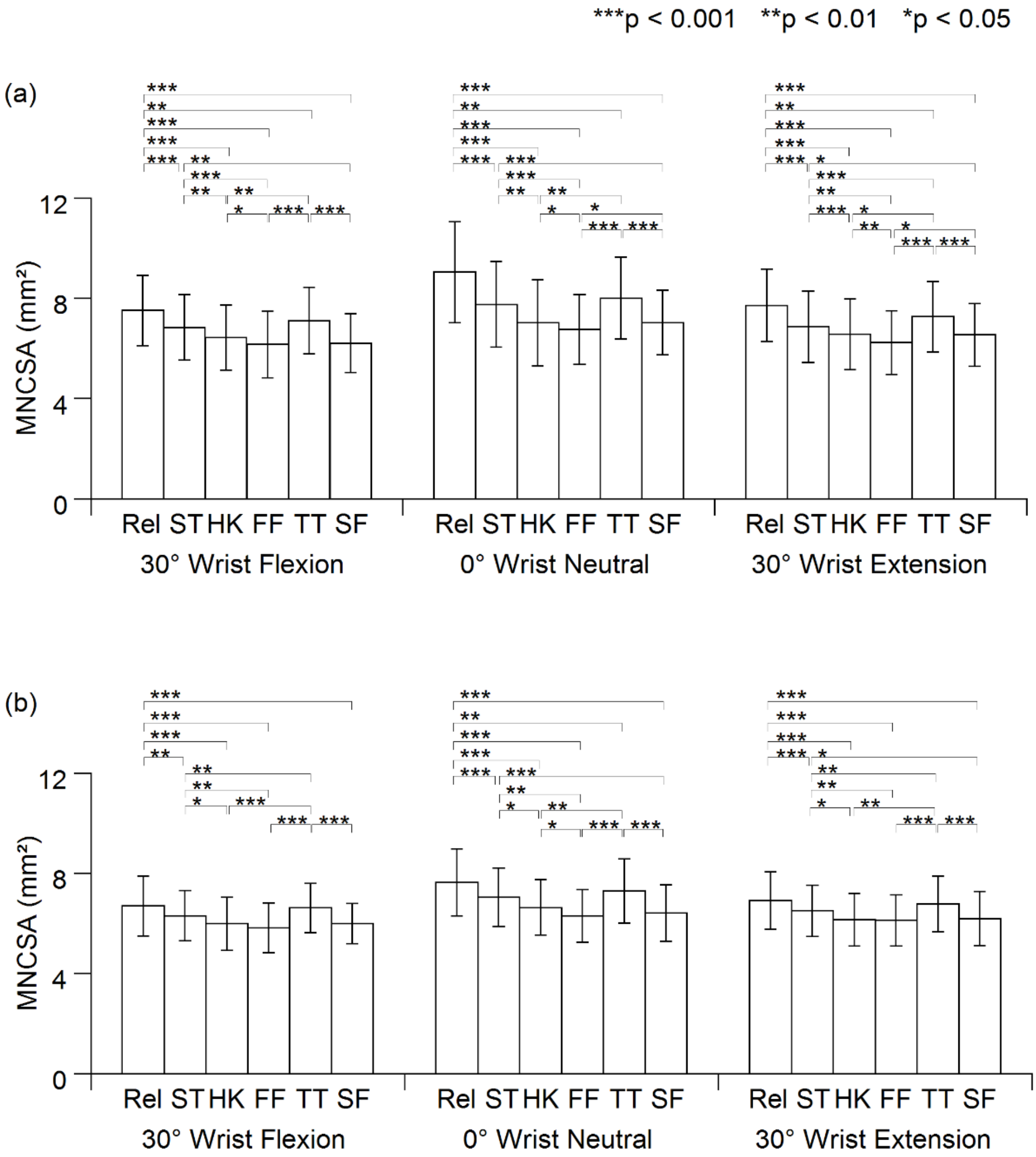

Figure 2.4 Median nerve cross-sectional area (MNCSA) of each finger position at (a) dominant, (b) nondominant hand.

Relaxed (Rel), straight finger (ST), hook (HK), full fist (FF), tabletop (TT), straight fist (SF).

Table 2.3 Median nerve cross-sectional area and diameters of each finger posture at different wrist angles.

Wrist angle	Finger postures					
	Relaxed	Straight	Hook	Full fist	Tabletop	Straight fist
Median nerve cross-sectional area (MNCSA, mm²)						
Dominant wrist						
30° Flex	7.5 ± 1.4 [a]	6.9 ± 1.3 [a]	6.4 ± 1.3 [a]	6.2 ± 1.3 [a]	7.1 ± 1.3 [a]	6.2 ± 1.2 [a]
0° Neutral	9.1 ± 2.0	7.8 ± 1.7	7.0 ± 1.5	6.8 ± 1.4	8.0 ± 1.7	7.0 ± 1.3
30° Ext	7.7 ± 1.4 [a]	6.9 ± 1.4 [a]	6.6 ± 1.4 [a]	6.3 ± 1.3 [a]	7.3 ± 1.4 [a]	6.5 ± 1.3 [a]
Nondominant wrist						
30° Flex	6.7 ± 1.2 [a]	6.3 ± 1.0 [a]	6.0 ± 1.1 [a]	5.8 ± 1.0 [a]	6.6 ± 1.0 [a]	6.0 ± 0.8 [b]
0° Neutral	7.6 ± 1.3	7.1 ± 1.2	6.6 ± 1.1	6.3 ± 1.1	7.3 ± 1.3	6.4 ± 1.1
30° Ext	6.9 ± 1.1 [a]	6.5 ± 1.0 [a]	6.2 ± 1.0 [a]	6.1 ± 1.0	6.8 ± 1.1 [a]	6.2 ± 1.1
Diameter in radial-ulnar direction (D1, mm)						
Dominant wrist						
30° Flex	4.4 ± 0.7 [a]	4.2 ± 0.8 [a]	4.2 ± 0.7 [b]	4.1 ± 0.8 [c]	4.5 ± 0.8 [a]	3.9 ± 0.8 [b]
0° Neutral	5.7 ± 0.8	5.3 ± 0.9	4.9 ± 0.6	4.5 ± 0.7	5.1 ± 0.7	4.7 ± 0.7
30° Ext	5.9 ± 0.8	5.1 ± 0.8	4.8 ± 0.7	4.5 ± 0.8	5.2 ± 0.8	4.5 ± 0.8
Nondominant wrist						
30° Flex	4.0 ± 0.6 [a]	4.0 ± 0.7 [a]	4.0 ± 0.7	4.1 ± 0.6 [c]	4.5 ± 0.7	3.9 ± 0.4
0° Neutral	5.2 ± 0.7	4.9 ± 0.7	4.6 ± 0.7	4.3 ± 0.6	4.9 ± 0.6	4.3 ± 0.6
30° Ext	5.6 ± 0.6 [a]	5.1 ± 0.7	4.7 ± 0.6	4.3 ± 0.6	4.9 ± 0.6	4.3 ± 0.7
Diameter in dorsal-palmar direction (D2, mm)						
Dominant wrist						
30° Flex	2.2 ± 0.3	2.1 ± 0.4 [b]	2.0 ± 0.4 [c]	1.9 ± 0.3	2.0 ± 0.3	2.1 ± 0.4
0° Neutral	2.1 ± 0.3	1.9 ± 0.3	1.8 ± 0.3	1.9 ± 0.3	2.0 ± 0.3	1.9 ± 0.3
30° Ext	1.6 ± 0.2 [a]	1.7 ± 0.2 [b]	1.7 ± 0.3	1.8 ± 0.2 [c]	1.8 ± 0.2 [a]	1.9 ± 0.3
Nondominant wrist						
30° Flex	2.2 ± 0.3 [a]	2.1 ± 0.4 [b]	1.9 ± 0.3	1.8 ± 0.3	1.9 ± 0.3	2.0 ± 0.3
0° Neutral	1.9 ± 0.2	1.8 ± 0.2	1.9 ± 0.3	1.9 ± 0.3	1.9 ± 0.3	1.9 ± 0.3
30° Ext	1.5 ± 0.1 [a]	1.7 ± 0.2 [a]	1.7 ± 0.2 [b]	1.8 ± 0.2 [c]	1.8 ± 0.2 [c]	1.9 ± 0.3

Flex: Flexion; Ext: Extension;

[a] $p < 0.001$, [b] $p < 0.01$, [c] $p < 0.05$, post-hoc Bonferroni with compared to the wrist neutral at each finger posture.

Table 2.4 Deformation percentage (%) of the median nerve cross-sectional area and diameters of each finger posture at different wrist angles.

Wrist angle	Finger postures					
	Relaxed	Straight	Hook	Full fist	Tabletop	Straight fist
Median nerve cross-sectional area (MNCSA, mm²)						
Dominant wrist						
30° Flex	-16.2	-23.6	-28.3	-31.6	-20.7	-30.5
0° Neutral	-	-14.1	-21.8	-25.0	-11.0	-21.5
30° Ext	-13.8	-23.7	-26.8	-30.6	-18.9	-27.0
Nondominant wrist						
30° Flex	-12.2	-16.9	-21.3	-23.3	-12.7	-20.7
0° Neutral	-	-7.4	-12.8	-17.3	-4.3	-15.7
30° Ext	-9.1	-14.2	-19.2	-19.5	-10.9	-18.6
Diameter in radial-ulnar direction (D1, mm)						
Dominant wrist						
30° Flex	-21.8	-26.3	-25.8	-27.8	-21.2	-30.8
0° Neutral	-	-6.5	-12.3	-20.5	-10.1	-17.5
30° Ext	4.1	-8.7	-14.7	-20.0	-7.7	-21.0
Nondominant wrist						
30° Flex	-23.5	-23.1	-21.6	-20.2	-13.2	-23.5
0° Neutral	-	-4.7	-10.2	-16.8	-4.9	-16.3
30° Ext	9.4	-1.9	-8.3	-16.0	-4.1	-16.8
Diameter in dorsal-palmar direction (D2, mm)						
Dominant wrist						
30° Flex	6.3	4.5	-2.5	-5.1	1.4	1.9
0° Neutral	-	-8.9	-11.2	-4.5	-1.4	-4.9
30° Ext	-19.7	-16.9	-15.2	-12.0	-12.4	-7.5
Nondominant wrist						
30° Flex	14.3	10.6	2.8	-1.8	1.8	6.4
0° Neutral	-	-2.1	-1.9	0.8	1.5	0.5
30° Ext	-18.0	-12.3	-10.9	-2.8	-6.4	-0.7

Flex: Flexion; Ext: Extension.

2.3.3 *Effect of the Finger Posture and Wrist Angle on the Changes in D1 and D2*

The results showed no significant interaction for both D1 and D2 in finger posture × wrist angle × handedness (D1, $p = 0.483$; D2, $p = 0.225$), finger posture × handedness (D1, $p = 0.197$; D2, $p = 0.548$), and wrist angle × handedness (D1, $p = 0.287$; D2, $p = 0.662$). However, the finger posture × wrist angle interaction was significant (D1, $p < 0.001$; D2, $p < 0.001$). Furthermore, the main effects of wrist angle (D1, $p < 0.001$; D2, $p < 0.01$) and finger posture (D1, $p < 0.001$; D2, $p < 0.01$) on the changes of median nerve diameters were significant. The mean values and the deformation percentages of D1 and D2 of all finger postures at three wrist angles are presented in Tables 2.3 and 2.4, respectively. As the finger postures change at neutral wrist, D1 becomes significantly shorter as the finger changes from relaxed to different finger postures. Then, D1 at straight finger and at tabletop are significantly longer, whereas D1 at full fist is significantly shortest among all postures (Fig. 2.5a and 2.5b). In comparison, D2 at straight finger and at hook are significantly shorter than at relaxed and tabletop (Fig. 2.5c).

In contrast to neutral wrist, wrist flexion caused significant reduction of D1 (Fig. 2.5a and 2.5b). With reference to D1 of the relaxed finger at neutral wrist, the deformation percentages of D1 at each finger posture are approximately -23%, except for tabletop (-13%) (Table 2.4). D1 at tabletop is longer among all finger postures. In addition, D2 generally became smaller as compared to relaxed finger, and full fist caused the highest deformation of D2 (Fig. 2.5c and 2.5d, Table 2.3). Similarly, tendon gliding movements at wrist extension caused different deformation trends in D1 and D2 with reference to those at neutral wrist. In general, D1 became smaller as the finger changed from relaxed finger to a different finger posture, and D1 at full fist is the shortest among all finger postures (Fig. 2.5a and 2.5b). Notably, the finger tendon gliding movements at wrist extension showed a different deformation trend of D2 in comparison to neutral wrist and wrist 30° flexion. D2 at relaxed finger is the shortest among all finger postures. The D2 length became longer as the relaxed finger changed to different finger postures, and the D2 lengths at full fist and straight fist are longer than those at other finger postures (Fig. 2.5c and 2.5d, and Table 2.3).

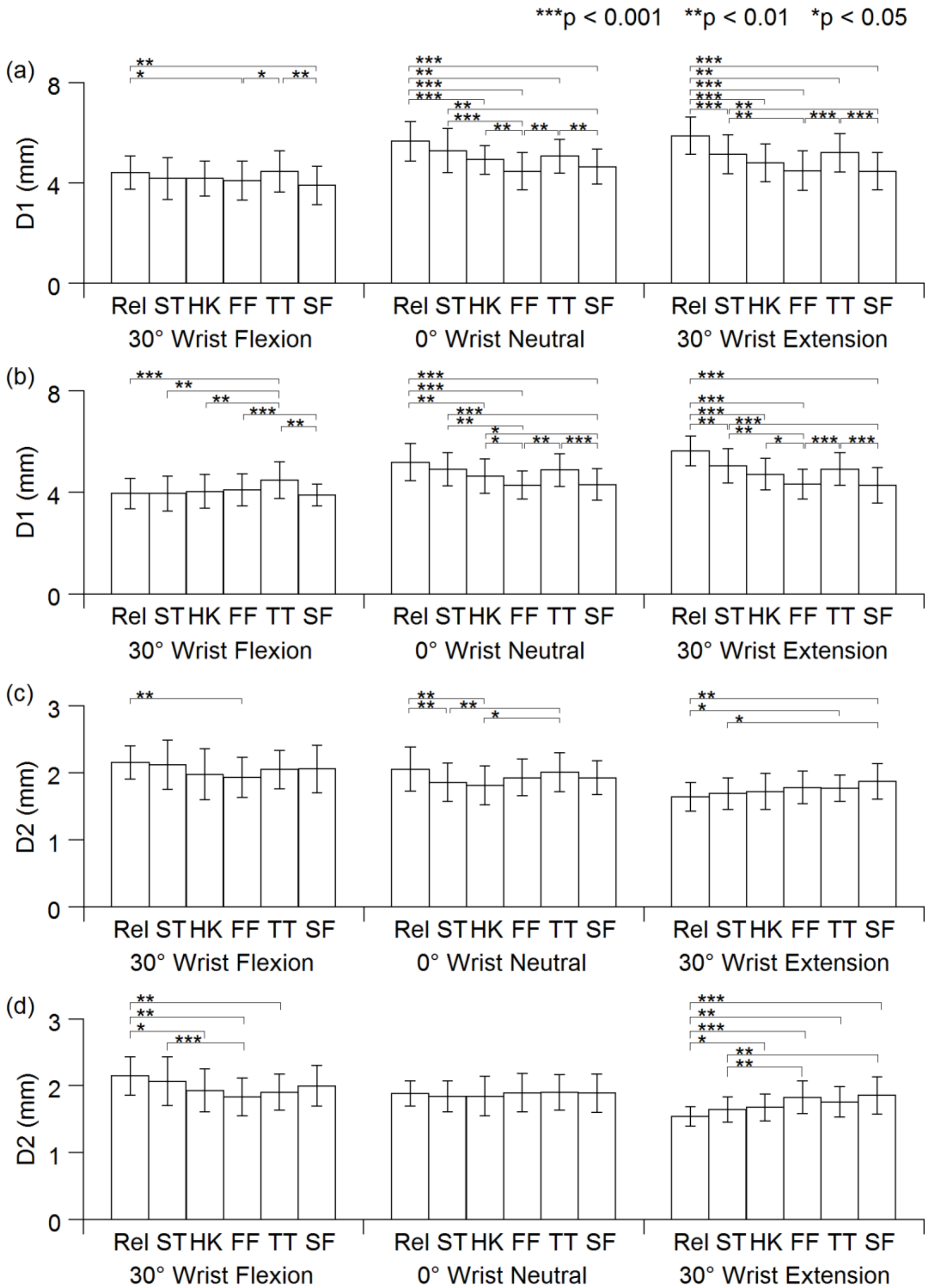

Figure 2.5 Median nerve diameters D1 and D2 of each finger position at (a), (c) dominant and (b), (d) nondominant hand.

D1, diameter in radial-ulnar direction; D2, diameter in dorsal-palmar direction.

Relaxed (Rel), straight finger (ST), hook (HK), full fist (FF), tabletop (TT), straight fist (SF).

2.4 Discussion

The carpal tunnel is a confined space, and the median nerve is unavoidably compressed due to the excursion and displacement of the tendons during finger movements. This study demonstrates the morphological changes of the median nerve, namely, MNCSA, D1, and D2, during the finger tendon gliding position at different wrist angles (Fig. 2.1). The finger movements are contributed to by the extrinsic flexor and extensor and intrinsic muscles of the hand. In addition to the absolute changes of the MNCSA, D1, and D2, the deformation percentage was calculated to present the changes of the median nerve during finger tendon gliding at different wrist angles.

First, the effect of different finger postures on the morphological changes of the median nerve at the neutral (0°) wrist position was examined. Generally, the results are in agreement with previous studies indicating that differential tendon gliding causes a variety of compression stress on the median nerve (Ugbolue et al., 2005; van Doesburg et al., 2012). Previous study reported no significant difference of the median nerve area when the fingers moved from extension to full fist (Yoshii et al., 2009). However, the results indicated the MNCSA was significantly reduced as the finger posture changed from relaxed to full fist (Fig. 2.4). This discrepancy could result from various factors such as different image acquisition protocols and the angle of the median nerve in the obtained images. The median nerve and flexor tendons displaced in a three-dimensional direction, transverse (radial-ulnar), vertical (dorsal-palmar), and longitudinal (distal-proximal), during finger and wrist movements (Lopes et al., 2011; Szabo et al., 1994; Wright, Glowczewskie, Wheeler, Miller, & Cowin, 1996). The MNCSA at both straight finger and tabletop postures showed lesser deformation among the tendon gliding postures (Fig 2.4). The extension of MCP and IP joints as the relaxed finger changed to straight finger could result in transverse contraction and elongation of the median nerve that causes the reduction of the MNCSA. Subsequently, the deformation of the MNCSA at tabletop is lesser than that of straight finger (Table 2.4). Previous studies suggest that the intrinsic muscles are the main flexors of the MCP joint, whereas the proximal-distal displacements of FDS and FDP resulting from the flexion of the MCP joints are less than those of hook, straight fist, and full fist (Koh, Buford Jr, Andersen, & Viegas, 2006; Ugbolue et al., 2005; Wehbé & Hunter, 1985). Therefore, the radial-ulnar displacements and lower excursion amplitude of the finger flexor tendons in straight finger and tabletop postures may associate with lower deformation on the MNCSA during active finger flexion movements.

FDS and FDP are the primary muscles that initiate the IP joint flexion in the hook and straight fist positions, whereas maximal excursion of the FDS and of the FDP are achieved at the full fist position (Kamper, George Hornby, & Rymer, 2002; Wehbé, 1987). The flexor tendons and median nerve glide smoothly with the surrounding subsynovial connective tissues. The shear strain of the subsynovial connective tissue at fist motion is higher than that at single digit motion (Yamaguchi, Osamura, Zhao, An, & Amadio, 2008). Longer excursions of the finger flexor tendons at hook and straight fist may cause higher transverse contraction and tensile stress to the median nerve in comparison with straight finger and tabletop (Fig. 2.4). The significant reduction of the MNCSA at full fist could be due to the increased of shear strain, which may limit the mobility of the median nerve (Coppieters & Alshami, 2007; Ettema, An, Zhao, O'Byrne, & Amadio, 2008; Yoshii, Ishii, & Sakai, 2013). Furthermore, the MCP joints at both straight fist and full fist are at almost the same angle, except for the DIP joint flexion at full fist. However, the deformation percentage of the MNCSA at full fist is much higher than that of hook and straight fist (Table 2.4). Along with the transverse contraction, the median nerve is passively displaced and nearer to the TCL with the transverse and vertical displacements of the flexor tendons. In addition, the increase of the carpal tunnel pressure from the incursion of lumbricals (Keir & Rempel, 2005) may result in a higher deformation ratio of the MNCSA. The median nerve images of each finger position at neutral wrist were presented in Figure 2.6.

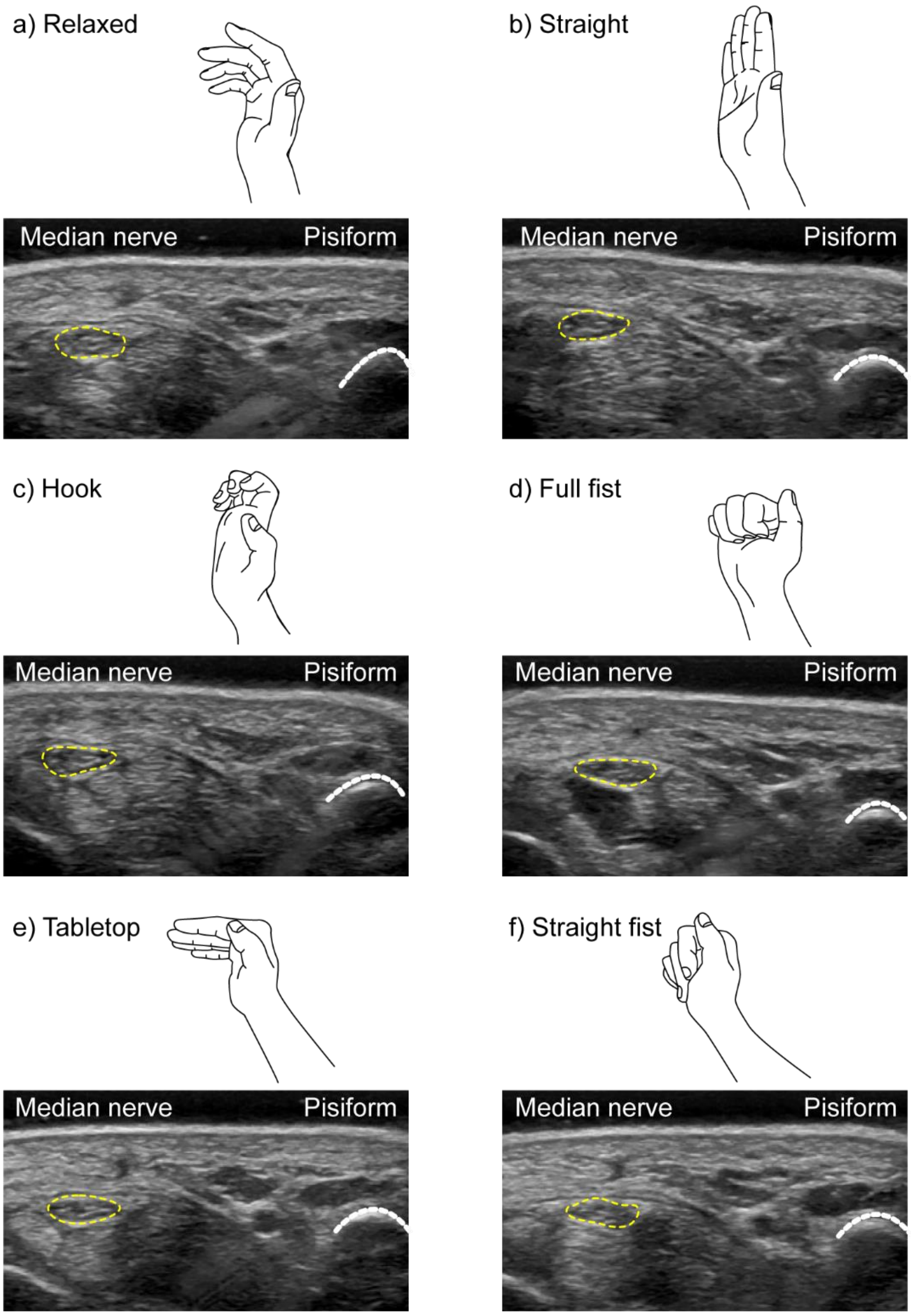

Figure 2.6 Ultrasound images of the median nerve at each finger position with neutral wrist.

Additionally, the effects of the wrist angle changes on the median nerve deformation during the finger tendon gliding position were examined. Wrist 30° flexion and 30° extension caused the MNCSA to be further deformed at all finger postures (Table 2.4). The results are in agreement with those of Loh and Muraki (2015), who indicated that wrist 30° flexion and extension cause the MNCSA to be deformed at approximately -15% at the relaxed finger posture (Table 2.4). The present study demonstrates that finger flexor tendon gliding at wrist flexion causes the highest deformation of the MNCSA, followed by wrist extension (Table 2.4). Wrist flexion and extension decrease the carpal tunnel volume, resulting in the displacement of the tendons and dorsal-palmar displacement of the median nerve in the carpal tunnel (Canuto et al., 2006; Keir & Wells, 1999; Martin et al., 2013; Mogk & Keir, 2008). Furthermore, the shear strain index of the subsynovial connective tissue increases with active finger movements at wrist flexion (Kursa, Lattanza, Diao, & Rempel, 2006; Yoshii et al., 2008). Results from this study suggest that both wrist flexion and extension led to higher deformation percentages of each finger posture in comparison to neutral wrist (Table 2.4). The higher deformation of the MNCSA at wrist flexion-extension likely due to the increased intra-carpal tunnel stress secondary to the excursion of flexor tendons through a narrower carpal tunnel.

The changes of D1 and D2 at neutral wrist for each finger posture were analyzed to understand the morphological changes of the median nerve in response to compression stress. The peripheral nerves such as the median nerve contain loose space within the epineural tube, allowing the nerve to adapt to biomechanical stress such as tensile and compressive stress or combination stresses, which may result from joint movements or external pressure (Keir & Rempel, 2005; Kociolek et al., 2015; Millesi et al., 1995; Topp & Boyd, 2006). D1 became significantly shorter as the finger changed from relaxed finger to different finger postures, except for tabletop. The greatest and least deformations of D1 occur at full fist and tabletop, respectively (Fig. 2.5 and Table 2.4). Similar to D1, D2 at tabletop is the least deformed among the finger postures. On the contrary, D2 at hook is significantly smallest among all finger postures (Table 2.4). The displacements of finger flexor tendons during wrist and finger movements are a combination of those in both radial-ulnar and dorsal-palmar directions and are not uniform (Keir & Wells, 1999). As a result of the tendons' displacement within the carpal tunnel, the shape of median nerve changes during wrist and finger movements (van Doesburg et al., 2012; Yoshii et al., 2013; Yoshii et al., 2013). In addition, the alteration of the rotational axis of the median nerve also occurs during the displacement of finger flexor tendons and it affects the quantification of D1 and D2.

The results from this study show agreement with previous studies in which wrist flexion and extension cause significant changes to D1 and D2 at relaxed finger, respectively (Table 2.3) (Loh & Muraki, 2015; Loh et al., 2015). Finger tendon gliding at wrist 30° flexion and extension results different deformation patterns of D1 and D2 (Fig. 2.5). At wrist flexion, D1 at tabletop is longest, and it becomes shorter as the finger changes from tabletop to other postures. The D2 length at full fist is significantly shorter in comparison to relaxed finger (Fig. 2.5). Therefore, the transverse displacement (radial-ulnar direction) of the flexor tendons during active tendon gliding at wrist flexion could result in high deformation percentages of D1 (Table 2.4). At wrist 30° extension, the least deformation of D1 among the flexor tendon gliding postures occurs with relaxed finger and tabletop, and the greatest deformation of D1 occurs at full fist. In contrast to D1, the least and greatest deformations of D2 occur at straight fist and relaxed finger, respectively. Additionally, finger movements at wrist extension produce higher vertical compression stress on the median nerve and result in greater deformation percentages of D2 (Table 2.4). However, the D2 length is gradually increased as the finger posture changes from straight finger to other finger postures at wrist extension (Fig. 2.5). One of the postulations is that the deformations of D1 and D2 at different finger postures are closely related to the geometry displacement of the flexor tendons inside the confined carpal tunnel.

The limitations in this study include the angle of the ultrasound transducer and the examination location. The ultrasound transducer was checked and placed perpendicularly to the wrist crease at all wrist angles during the examination. However, the angle of the ultrasound transducer could have changed slightly as the participants actively held the wrist and finger postures. Tilting of the ultrasound transducer towards the wrist crease results in an oblique cross-sectional image of the carpal tunnel, which affects the accuracy of the quantification of the median nerve. Subsequently, the median nerve was examined at wrist crease in this study. Greater median nerve deformation may occur at the mid-carpal tunnel or distal edge of the carpal tunnel because of carpal tunnel volume and higher inlet pressure during active tendon gliding. In addition, because the holding force while maintaining finger postures was not standardized, the absolute changes of the median nerve may be affected by individual differences. A previous study reported the intrusion of the lumbrical muscles (16.6 ± 18.5 mm) into the distal carpal tunnel with full active wrist flexion and full active finger flexion among non-CTS participants (N = 632) (Cartwright et al., 2014). In comparison, the images were acquired with minimal effort at active wrist 30° flexion-extension and active full fist. Generally, no well-defined lumbrical muscles were observed in the recorded images. Therefore, the muscle force of the full finger flexor muscles and wrist at flexion angle are the influential variables that should be taken into consideration, as it could affect the intrusion of lumbricals into the carpal tunnel. Further investigations are needed to understand the three-dimensional displacement of the flexor tendons and deformation of the median nerve during finger tendon gliding movements.

2.5 Conclusion

An understanding of the mechanical stress from wrist and finger joint movements on the median nerve is essential for the prevention of CTS. This study demonstrated the effects of finger tendon gliding movements on the deformation of the MNCSA at wrist 30° flexion, neutral wrist (0°), and wrist 30° extension. Differential gliding of the FDS and of the FDP at each finger posture cause the reduction of MNCSA compared to relaxed finger. Additionally, the changes of D1 and D2 are sensitive to each finger posture at all three wrist angles. The deformation of the median nerve at each finger posture is greater as the wrist angle deviates from the neutral position. Further studies are needed for a better understanding of the impact of different combinations of the wrist–finger movements on the median nerve.

Chapter 3 Impacts of Grip Force at Different Wrist Angles on the Median Nerve

3.1 Introduction

Carpal tunnel syndrome (CTS) is one of the most common peripheral neuropathies associated with socioeconomic burden (K. T. Palmer et al., 2007), and the quality of life of CTS patients has been shown to be affected by the clinical symptoms of CTS (Atroshi, Gummesson, Johnsson, & Sprinchorn, 1999). Work-related musculoskeletal disorders of the upper extremities, such as CTS, have been shown to be associated with biomechanical risk factors, such as grip force exertion during forceful hand tasks, repetitive joint movements, and wrist postures (Bao et al., 2015; Harris-Adamson et al., 2015; Violante et al., 2007; You, Smith, & Rempel, 2014). Furthermore, finger movements and fingertip loading are known to cause an increase in intra-carpal tunnel pressure (Kursa, Diao, Lattanza, & Rempel, 2005; Kursa et al., 2006; Smith, Sonstegard, & Anderson, 1977). Therefore, repetitive forceful finger activities may increase the risk of CTS.

Furthermore, the non-neutral wrist posture has been shown to be associated with an overall high risk of CTS (You et al., 2014). Flexed and extended wrist posture can lead to changes in the shapes of the carpal tunnel, as well as the displacement of the median nerve, finger flexor tendons and stiffness of the transverse carpal ligament (Bower et al., 2006; Holmes et al., 2011). MRI studies have suggested that wrist flexion/extension can decrease the volume of the carpal tunnel when compared to neutral wrist postures (Mogk & Keir, 2008; Mogk & Keir, 2009). Furthermore, wrist flexion and extension movements cause three-dimensional displacement of the median nerve and finger flexor tendons, namely proximal-distal, radial-ulnar, and dorsal-palmar displacements (Canuto et al., 2006; Wang et al., 2014; Yoshii et al., 2008; Yoshii et al., 2013). Subsequently, changes in wrist posture and finger movements can also influence finger flexor tendons geometry within the carpal tunnel (Keir & Wells, 1999; Martin et al., 2013). In response to the contact pressure arising from finger flexor tendon displacement, the median nerve deforms in order to adapt to the biomechanical stress (Wang et al., 2014). Deformations of the cross-sectional area and diameter of the median nerve have been reported with changes in wrist posture and finger movement via ultrasound studies (Loh et al., 2015; Loh & Muraki, 2015; Wang et al., 2014; Yoshii et al., 2013).

The median nerve is located beneath the transverse carpal ligament and is exposed to mechanical stresses such as contact pressure from the flexor digitorum superficialis (FDS) and flexor digitorum profundus (FDP), and external compression pressure. Previous studies described the geometry changes of the finger flexor tendons with both wrist and finger movements as well as deformation of the median nerve under stress loading using ultrasound imaging (Ugbolue et al., 2005; van Doesburg et al., 2010; Yoshii et al., 2013). The median nerve parameters such as cross-sectional area becomes smaller at both full flexion of four fingers and single finger flexion (van Doesburg et al., 2012). For instance, independent middle finger flexion results in the FDS tendon displaced palmarly towards the transverse carpal ligament and creates contact stress on the median nerve (Yoshii et al., 2009). In addition, maximal finger flexion and forceful grip could increase the finger flexor tendon load (Keir, Wells, Ranney, & Lavery, 1997) and lead to incursion of the lumbrical muscles into the carpal tunnel (Cartwright et al., 2014; Cobb, An, Cooney, & Berger, 1994; Cobb, An, & Cooney, 1995), which can cause the cross-sectional area of the median nerve to become smaller when compared to the area with only wrist and/or finger movements.

The impacts of power grip or forceful clenched fist on changes to median nerve deformation are still remain unclear and questionable. The clenched fist posture or forceful finger flexion posture could lead to a higher deformation of the median nerve compared to individual finger flexion or unclenched fist conditions. In addition, the deformation of the median nerve at unclenched and clenched fist conditions at different wrist angles may demonstrate a different trend due to the changes of carpal tunnel size. The primary objective of the present study was to investigate the impact of three types of grip conditions (finger relaxation, unclenched fist, and clenched fist) (Fig. 3.1) on changes in the median nerve cross-sectional area (MNCSA) and median nerve diameter in the radial-ulnar direction (D1) and dorsal-palmar direction (D2) at three wrist angles. The first hypothesis is the MNCSA and median nerve diameter will become smaller with an unclenched and clenched fist, relative to finger relaxation at a neutral wrist position. Secondly, wrist extension and flexion will cause the MNCSA and median nerve diameter to become smaller, compared to the neutral wrist condition. Next, the grip strength of the dominant hand would be stronger than the nondominant hand at three wrist angles.

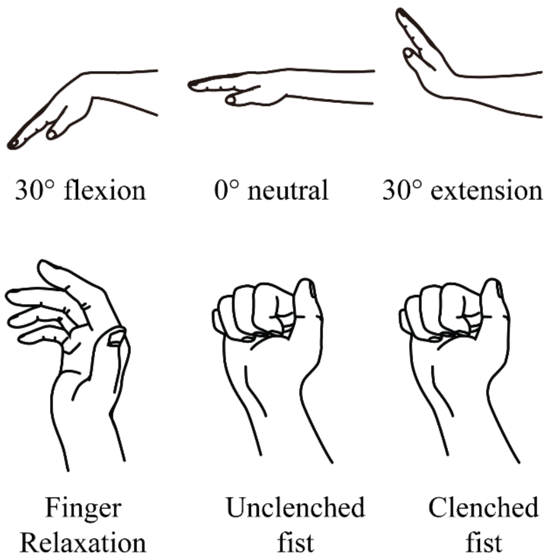

Figure 3.1 Grip conditions and wrist angles for ultrasound examination.

Finger relaxation, the fingers are rest in natural curvature; Unclenched fist, full fingers flexion and hold with minimal effort; Clenched fist, full fingers flexion and exert force to grip.

3.2 Materials and Methods

3.2.1 Participants

Twenty-nine healthy young adults (Table 3.1) without known upper limb musculoskeletal disorders were recruited. The handedness of the participants was determined with the Edinburgh Handedness Inventory (Oldfield, 1971). The participants provided written informed consent, and this study was approved by the Ethics Committee of the Faculty of Design, Kyushu University (Approval number 141).

Table 3.1 Characteristics of the participants (n = 29).

		Male (n = 19)	Female (n = 10)
Age (years)		24.2 ± 1.6	24.0 ± 1.6
Height (cm)		171.5 ± 4.7	159.1 ± 4.7
Weight (kg)		61.7 ± 6.0	48.9 ± 6.4
BMI (kg/m2)		21.0 ± 2.1	19.3 ± 2.1
Handedness (Right : Left hand dominant)		18 : 1	8 : 2
Grip strength (kgf)			
30° wrist	Dominant hand	23.6 ± 5.8	11.8 ± 2.1
flexion	Nondominant hand	20.1 ± 4.6	12.3 ± 2.4
Neutral wrist	Dominant hand	28.9 ± 6.8	15.8 ± 2.9
(0°)	Nondominant hand	25.6 ± 6.2	14.9 ± 3.3
30° wrist	Dominant hand	33.8 ± 7.5	19.2 ± 4.5
extension	Nondominant hand	29.9 ± 6.9	17.5 ± 4.2

3.2.2 Grip Strength Assessment

The grip strength of the participants was assessed using the digital grip strength dynamometer Grip-D (T.K.K. 5401; Takei Scientific Instruments Co., Ltd., Niigata, Japan). With the intention of simulating clenched fist with full interphalangeal joint flexion, the grab bar of the dynamometer was positioned at level 4 during grip strength assessment. The participants positioned the forearm in mid-pronation on an arm support during the grip assessment. A wrist goniometer (Exacta^{TM}, North Coast Medical Inc., Morgan Hill, CA) was used to determine the wrist angle. The axis point of the goniometer was placed at the triquetrum, while static and movable bars were placed parallel to the ulna bone and 5th metacarpal bone, respectively. The goniometer was used to determine the wrist angle before the grip strength assessment and to ensure that the wrist was maintained at the designated angle during the grip strength assessment. The grip strength of both the dominant and nondominant hands were measured thrice at three wrist positions (wrist flexion [30°], neutral position [0°], and wrist extension [30°]). The mean of the three grip strength measurements was calculated for each wrist position (Table 3.1).

3.2.3 Ultrasound Examination Protocol

The LOGIQ e ultrasound system (GE Healthcare, Milwaukee, WI) with a 12L-RS transducer (imaging frequency bandwidth of 5–13 MHz) was used to examine the wrist. A 7.0-mm-thick sonar pad (Nippon BXI Inc., Tokyo, Japan) was used as a coupling agent during the ultrasound examination. The examiner placed the ultrasound transducer gently on the sonar pad to avoid compression pressure at the wrist during the examination. The forearm was positioned in supination and rested on an arm support on a table, with the elbow at 30° flexion, during the ultrasound examination. The examiner placed the ultrasound transducer parallel to distal wrist crease to identify the median nerve in the transverse plane, with the pisiform as the anatomical landmark in all conditions. A custom made L-shape frame was used to assist the examiner to place the transducer perpendicularly to the wrist. Similar to the approach in the grip strength assessment, a wrist goniometer was placed at the ulnar side of the wrist and was used to position the wrist at the designated angle for each image. In addition, the ultrasound transducer was removed and repositioned, and wrist angle was re-measured before each image was obtained. The following three grip conditions were examined: finger relaxation (control condition), unclenched fist, and clenched fist (Fig. 3.1). Three images were taken for each posture at 30° wrist flexion, in the neutral position (0°), and at 30° wrist extension for both the dominant and nondominant hands.

3.2.4 Image Processing and Analysis

The MNCSA, D1, and D2 (Fig. 3.2) were quantified using ImageJ software (National Institutes of Health) (C. A. Schneider et al., 2012). The median nerve was identified as a hyperechoic structure in the transverse plane (Kele, 2012), and then, the MNCSA was quantified with the tracing method (Duncan et al., 1999). Subsequently, the examiner traced the median nerve along the hyperechogenic rim, and then, the longest diameter in the radial-ulnar direction (D1) and dorsal-palmar direction (D2) were identified by two perpendicular straight lines within the outlined median nerve (Fig. 3.2). This quantifying method was found to have good to excellent inter- and intra-rater reliabilities in a previous study (Loh & Muraki, 2015). The mean of three images was calculated for the MNCSA, D1, and D2 at each finger posture. The deformation percentages of the MNCSA, D1, and D2 were calculated using the following equation:

$$\text{Deformation Percentage} = \frac{\begin{array}{c}(\text{Measurement at different grip condition} - \\ \text{Measurement at finger relaxation at neutral wrist})\end{array}}{(\text{Measurement at finger relaxation at neutral wrist})} \times 100\%$$

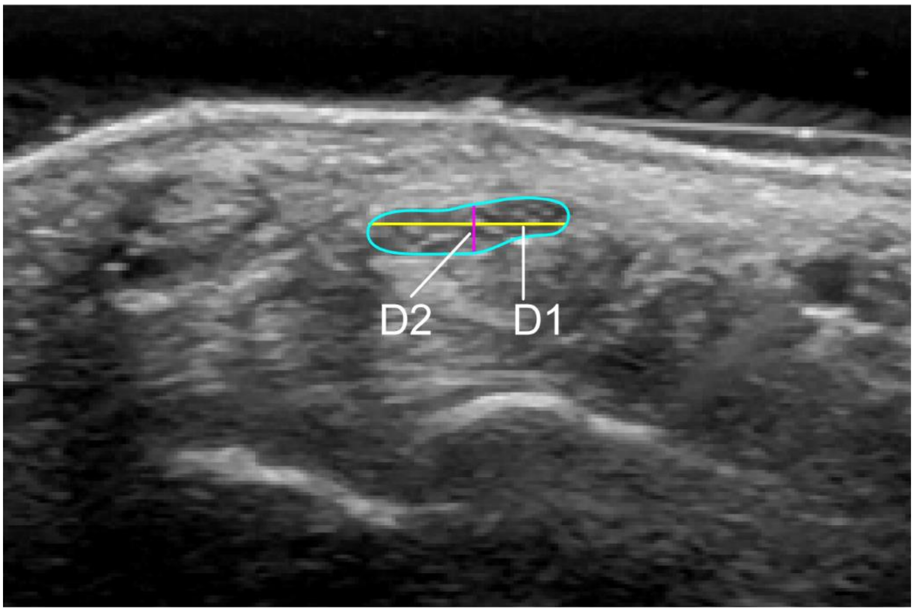

Figure 3.2 Quantification of the median nerve cross-sectional area (MNCSA), and median nerve diameter, D1 and D2.

3.2.5 Statistical Analysis

Two-way repeated analysis of variance (3 × 2 factorial design) was performed with three wrist angles (30° flexion, neutral [0°], and 30° extension) and hand dominance (dominant and nondominant) as factors to examine differences in the grip strength.

The sample characteristics of the MNCSA was examined with the Shapiro-Wilk's normality test (Razali & Wah, 2011; Shapiro & Wilk, 1965). Two-way repeated analysis of variance (3 × 3 factorial design) was performed with three grip conditions (finger relaxation, unclenched fist, and clenched fist), and three wrist angles (30° flexion, neutral [0°], and 30° extension) as factors to examine differences in MNCSA, D1, and

D2. Post-hoc pairwise Bonferroni-corrected comparison was performed to examine the significant effects. Significance was set at $\alpha = 0.05$. All statistical analyses were performed using SPSS version 21.0 software (IBM Corp., Armonk, NY). All results are presented in mean ± standard deviation.

3.3 Results

3.3.1 Grip Strength at Different Wrist Angle

The main effect of wrist angle on the change of grip strength was significant ($p < 0.01$). The grip strength at neutral wrist was significantly stronger ($p < 0.05$) than that at 30° wrist flexion but significantly weaker ($p < 0.01$) than that at 30° wrist extension. However, the main effect of hand dominance was not significant.

3.3.2 Sample Characteristics

The MNCSAs were approximately normally distributed in the Shapiro-Wilk's test ($p > 0.05$), and the samples were slightly skewed and kurtotic on visual inspection of histograms, normal Q-Q plots, and box plots (Table 3.2).

Table 3.2 Normality test for the median nerve cross-sectional area.

Skewness (M ± SE)	Kurtosis (M ± SE)	Shapiro-Wilk Test (p value)
0.44 ± 0.31	0.23 ± 0.62	0.490

M: mean, SE: standard error

3.3.3 *Effect of Grip Conditions and the Wrist Angle on the Change in the MNCSA*

The main effects of the grip condition ($p < 0.001$) and wrist angle ($p < 0.001$) on the change in the MNCSA were significant. Furthermore, a significant interaction was found between the grip condition and wrist angle ($p < 0.01$). The MNCSA significantly reduced as finger relaxation changed to unclenched fist and clenched fist conditions at all three wrist angles (Fig. 3.3a). The MNCSA at clenched fist was the smallest among the three grip conditions. The MNCSA was significantly smaller at wrist flexion (30°) and extension (30°) than in the neutral position (0°) in each grip condition (Table 3.3a). The deformations caused by unclenched fist and clenched fist conditions were approximately −20% and −30%, respectively (Table 3.4a) for the three wrist angles.

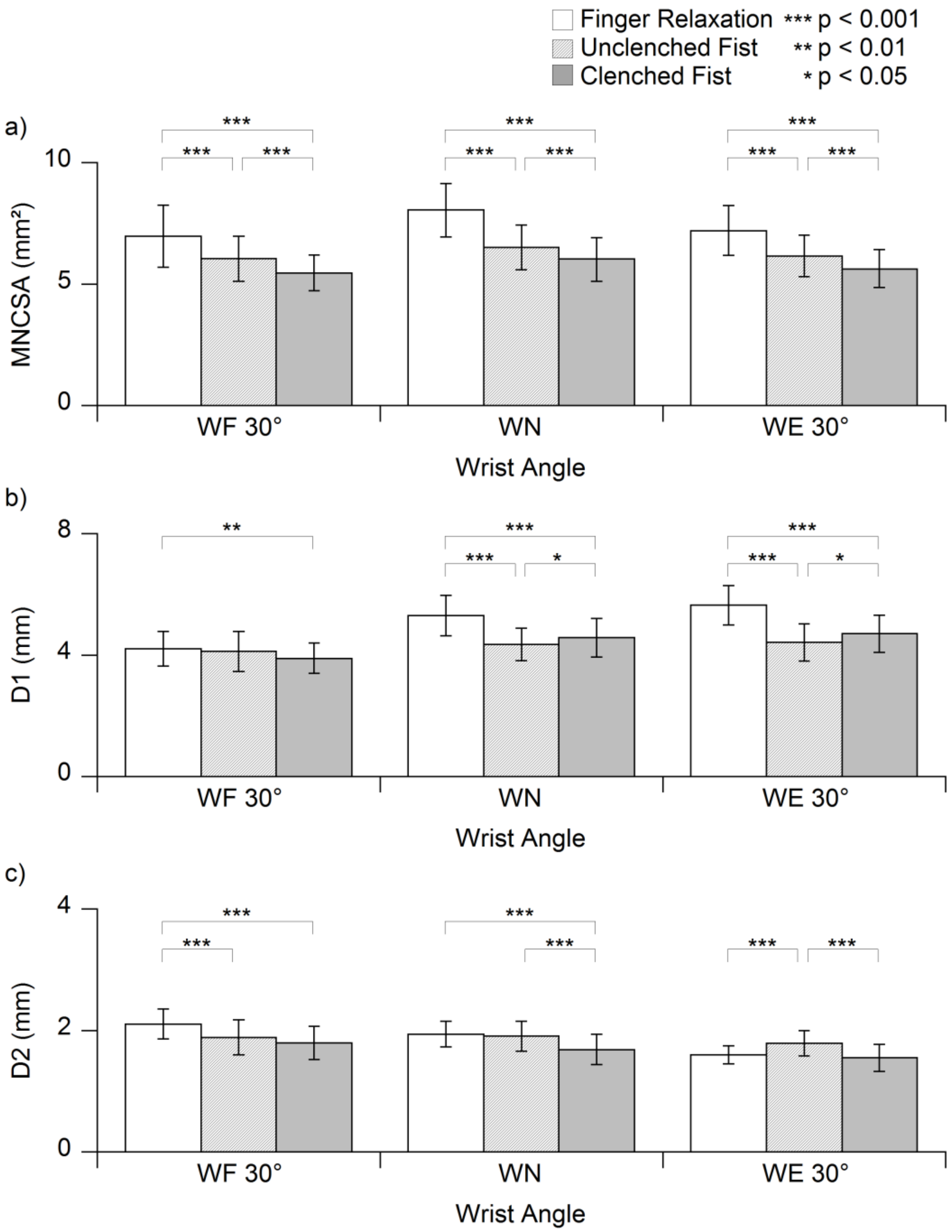

Figure 3.3 Mean value of the (a) median nerve cross-sectional area (MNCSA), (b) longitudinal diameter (D1) and (c) vertical diameter (D2) of finger relaxation, unclenched fist and clenched fist at three wrist angles.

WF, wrist flexion; WN, wrist neutral; WE, wrist extension; MNCSA, median nerve cross-sectional area; D1, diameter in radial-ulnar direction; D2, diameter in dorsal-palmar direction.

Table 3.3 Median nerve cross-sectional area and diameters of each grip condition at different wrist angle.

Wrist angle	Grip Conditions		
	Finger Relaxation	Unclenched Fist	Clenched Fist
(a) Median nerve cross-sectional area (MNCSA, mm^2)			
30° Flexion	7.0 ± 1.0^{a}	6.0 ± 0.9^{a}	5.5 ± 0.7^{a}
0° Neutral	8.1 ± 1.3	6.5 ± 0.9	6.0 ± 0.9
30° Extension	7.2 ± 1.1^{a}	6.2 ± 0.9^{a}	5.6 ± 0.8^{a}
(b) Diameter in radial-ulnar direction (D1, mm)			
30° Flexion	4.2 ± 0.6^{a}	4.1 ± 0.7^{c}	3.9 ± 0.5^{b}
0° Neutral	5.3 ± 0.7	4.4 ± 0.5	4.6 ± 0.6
30° Extension	5.6 ± 0.7^{b}	4.4 ± 0.6	4.7 ± 0.6
(c) Diameter in dorsal-palmar direction (D2, mm)			
30° Flexion	2.1 ± 0.2^{c}	1.9 ± 0.3	1.8 ± 0.3^{c}
0° Neutral	1.9 ± 0.2	1.9 ± 0.3	1.7 ± 0.3
30° Extension	1.6 ± 0.1^{c}	1.8 ± 0.2^{c}	1.6 ± 0.2^{c}

^{a} $p < 0.001$, ^{b} $p < 0.01$, ^{c} $p < 0.05$, post-hoc Bonferroni with compared to the wrist neutral at each grip.

Table 3.4 Deformation percentage (%) of the median nerve cross-sectional area and diameters of each grip conditions at different wrist angles.

Wrist angle	Grip Conditions		
	Finger Relaxation	Unclenched Fist	Clenched Fist
(a) Median nerve cross-sectional area (MNCSA, mm²)			
30° Flexion	−12.8	−18.7	−31.7
0° Neutral	NA	−22.9	−24.5
30° Extension	−10.1	−22.9	−29.5
(b) Diameter in radial-ulnar direction (D1, mm)			
30° Flexion	−20.3	−21.9	−25.7
0° Neutral	NA	−17.3	−12.8
30° Extension	6.7	−16.2	−10.4
(c) Diameter in dorsal-palmar direction (D2, mm)			
30° Flexion	9.3	−2.1	−6.8
0° Neutral	NA	−0.9	−12.5
30° Extension	−17.0	−6.9	−19.4

3.3.4 Effect of Grip Conditions and the Wrist Angle on the Changes in D1 and D2

The main effects of the grip condition (D1, $p < 0.01$; D2, $p < 0.01$) and wrist angle (D1, $p < 0.01$; D2, $p < 0.01$) on the changes in the median nerve diameter were significant. Furthermore, a significant interaction was found between the grip condition and wrist angle for both D1 and D2 (D1, $p < 0.001$; D2, $p < 0.001$). Generally, D1 significantly reduced as finger relaxation changed to unclenched fist or clenched fist conditions (Fig. 3.3b). Similarly, D2 significantly reduced as finger relaxation changed to unclenched fist or clenched fist conditions, except at 30° wrist extension (Fig. 3.3c). At

30° wrist extension, D2 was significantly higher at unclenched fist condition than at finger relaxation and clenched fist condition (Fig. 3.3c).

Additionally, the wrist angle changes caused significant deformation of D1 and D2 in each grip condition. D1 reduced as the wrist angle changed from 30° extension to neutral (0°) and from neutral (0°) to 30° flexion (Table 3.3b). In contrast, D2 increased as the wrist angle changed from 30° extension to neutral (0°) and from neutral (0°) to 30° flexion (Table 3.3c). In general, the highest deformation percentage of D1 was at 30° flexion (approximately −25%) (Table 3.4b), while the highest deformation percentage of D2 was at 30° extension (approximately −19%) (Table 3.4c).

3.4 Discussion

3.4.1 Effects of Grip Conditions on the Changes in the MNCSA, D1, and D2 in the Neutral Wrist Position (0°)

Biomechanics factors for injury in workplace, such as hand force and wrist posture, are known to be risk factors for CTS among workers (Burt et al., 2013). The differential excursion amplitude of the finger flexor tendons and the force exertion of the finger flexor muscles could contribute to the changes in median nerve tension and intra-carpal tunnel pressure, and thus affect the deformation of the median nerve.

In this study, the changes of the MNCSA and the median nerve diameter among finger relaxation, unclenched fist, and clenched fist conditions were investigated (Fig. 3.1) in the neutral wrist position (0°) by ultrasound imaging technique among healthy young adults. A significant reduction in the MNCSA was found as the fingers changed from finger relaxation to unclenched fist condition (Fig. 3.3a), which may have resulted from mechanical stress arising from the radial-ulnar displacement of the finger flexor tendons within the carpal tunnel (van Doesburg et al., 2010). Subsequently, a further reduction in the MNCSA was observed as the fingers changed from unclenched fist condition to clenched fist condition (Fig. 3.3a). The maximal excursion and displacement of both the FDS and FDP secondary to the finger flexor muscles bellies contraction might have caused further transverse contraction stress to the median nerve within the confined carpal tunnel space. The higher deformation percentage of the MNCSA at clenched fist condition (Table 3.4a) indicates the cross-sectional area of median nerve becomes smaller which could have resulted from an increase in the intra-carpal tunnel pressure caused by maximal excursion of the finger flexor tendons at clenched fist condition (Goss & Agee, 2010).

The changes in D1 and D2 at different grip conditions in the neutral wrist position (0°) were analyzed. Both D1 and D2 were significantly lower at unclenched fist and clenched fist conditions than at finger relaxation (Figs. 3.3b and 3.3c). Interestingly, clenched fist conditions did not result in the highest deformations of both D1 and D2 (Fig. 3.3). The highest deformations of D1 and D2 were at unclenched fist and clenched fist conditions, respectively (Table 3.4b and 3.4c). This phenomenon may have been caused by contact stress from the finger flexor tendons within the carpal tunnel and the different elongation degrees of the median nerve at each grip condition. The active contraction of FDS and FDP during clenched fist condition caused a greater change in median nerve diameter than the unclenched fist condition. Consequently, elongation of the median nerve secondary to clenched fist condition may affect the changes in D2 compared to unclenched fist condition at neutral wrist position. Therefore, the finger flexion force may be one of the important factors contributing to the dynamic changes in the median nerve diameter, as observed at unclenched fist and clenched fist conditions (Figs. 3.3b and 3.3c).

3.4.2 Effects of Grip Conditions and the Wrist Angle on Changes in the MNCSA, D1, and D2

The space within the epineural tube of peripheral nerves is crucial for the nerve to adapt to the external mechanical stress from surrounding structures. The median nerve is displaced and slides between the finger flexor tendons, and its shape is altered in response to irregular displacement of the finger flexor tendons within the carpal tunnel. The effects of wrist angle on changes to the median nerve in different grip conditions was analyzed to address the second hypothesis.

At finger relaxation, the MNCSA was significantly lower at 30° wrist flexion and 30° wrist extension than in the neutral wrist position (0°) (Table 3.3a). The reductions in the MNCSA caused by wrist flexion and extension are consistent with the findings of previous studies that showed deformation of the median nerve caused by wrist movements in young and old adults (Loh & Muraki, 2015). Furthermore, the MNCSA significantly reduced as the wrist changed from neutral (0°) to 30° flexion and 30° extension (Table 3.3a) at both unclenched fist and clenched fist conditions (Fig. 3.1). Additionally, at unclenched fist and clenched fist conditions, the deformation percentages of the MNCSA were higher at 30° wrist flexion and 30° wrist extension than in the neutral wrist position (0°) (Table 3.4a). Previous studies have shown that the carpal tunnel volume is lower at wrist flexion and extension that in the neutral wrist position (0°) (Mogk & Keir, 2008). The gliding amplitude of the finger flexor tendons increased during the clenched fist condition, and this could lead to incursion of the lumbrical muscles into the distal carpal tunnel (Cobb et al., 1994). Gliding of the finger flexor tendons in a small carpal tunnel and incursion of lumbrical muscles into the carpal tunnel could substantially increase the intra-carpal tunnel pressure and result in high deformation of the MNCSA (Table 3.4a).

The results are consistent with those of previous studies showing that wrist flexion causes significant changes in D1 at finger relaxation (Loh & Muraki, 2015). D1 was significantly lower at 30° wrist flexion and was significantly higher at 30° wrist extension than in the neutral wrist position (0°) at finger relaxation (Table 3.3b). Additionally, 30° wrist flexion and 30° wrist extension resulted in a further reduction in D1 at unclenched fist and clenched fist conditions (Table 3.3b). Furthermore, wrist flexion resulted in a further significant reduction in D1 at clenched fist condition but not at unclenched fist condition (Table 3.4b). Although D1 showed a decreasing trend at wrist flexion with unclenched fist condition, there was no significant difference on comparing wrist flexion with the neutral wrist position (Table 3.4b). Notably, the deformation of D1 in all the three grip conditions was higher at 30° wrist flexion than at the other wrist angles (Table 3.4b). This further reduction of D1 could possibly have resulted from the changes of geometry arrangement of the finger flexor tendons within a smaller carpal tunnel at wrist flexion and extension.

In contrast, D2 was significantly lower at finger relaxation and clenched fist condition than at unclenched fist condition at 30° wrist extension (Fig. 3.3c). The deformation percentages of D2 were generally lower than the deformation percentages of D1 in all grip conditions and at all wrist angles, and the largest deformation percentage was approximately −20% (Table 3.4c). This reduction in D2 could have resulted from elongation and the presence of transverse contraction stress at the median nerve. The stiffness of the transverse carpal ligament has been reported to be higher at wrist flexion than at wrist extension and in the neutral wrist position (Holmes, Howarth, Callaghan, & Keir, 2012). The D2 was significantly higher at unclenched fist condition than at both finger relaxation and clenched fist condition at 30° wrist extension (Fig. 3.3c). The low stiffness of the transverse carpal ligament at 30° wrist extension (Holmes et al., 2011) might have resulted in low dorsal-palmar stress on the median nerve at unclenched fist condition.

The present study has some limitations. First, the rotational axis of the median nerve could not be identified owing to the image acquisition protocol. The displacement of the finger flexor tendons could lead to changes in the rotational axis of the median nerve and could affect the quantification of median nerve diameter. The rotational effects of the median nerve should be considered in future studies. Second, hand dominance does not affect grip strength at different wrist angles. The measured grip strengths among both male and female participants in the present study (Table 3.1) were approximately 40–50% lower than the reported normative data (Dodds et al., 2014; Dodds et al., 2016; Massy-Westropp, Gill, Taylor, Bohannon, & Hill, 2011; Nagasawa, Demura, & Hamazaki, 2010). The lower grip strength data obtained in this study most likely resulted from the low grab bar position of the dynamometer and the forearm posture during grip strength assessment, which was different from the posture during grip strength assessment reported previously (Massy-Westropp et al., 2011). A higher grip force exertion could lead to a higher compression stress to the median nerve which results in further decrease of MNCSA. Future studies with different power grip span is needed to investigate the impact of gripping force on the median nerve deformation.

3.5 Conclusion

The median nerve deforms with finger flexion movements, while clenched fist condition contributes to higher deformation percentages of median nerve parameters. Furthermore, wrist angle was identified as an important factor that could affect the deformability of the median nerve in unclenched and clenched fist conditions. In summary, wrist flexion and extension can lead to higher deformation of the MNCSA, and wrist flexion and extension influence the deformation of both D1 and D2, respectively. Future studies are needed to further explore the impacts of grip and the kinematic changes of the finger flexor tendons on the deformation of the median nerve, with special consideration of median nerve mobility.

Chapter 4 Effects of Computer Keyboard Typing on the Median Nerve

4.1 Introduction

Computer technology is evolving rapidly, and the computer has become one of the essential tools used in daily work in most industries. The literature suggests that computer users are expose to a high risk of upper musculoskeletal symptoms and work-related musculoskeletal disorders (Dennerlein & Johnson, 2006; Gerr, Monteilh, & Marcus, 2006; Huysmans et al., 2012). Furthermore, the amount of time spent on the computer is associated with a high incidence of musculoskeletal disorders (Gerr et al., 2002; Gerr, Marcus, & Monteilh, 2004; Marcus et al., 2002).

Carpal tunnel syndrome (CTS) is one of the most common peripheral neuropathies among work-related musculoskeletal disorders (Dias et al., 2004; Mediouni et al., 2015; Newington, Harris, & Walker-Bone, 2015). CTS occurs when the median nerve is compressed at the carpal tunnel, and it not only affects the quality of life of individuals, but also has a huge impact on social burden and the economy (Atroshi et al., 1999; Coggon et al., 2013; D. H. Palmer & Hanrahan, 1995). Biomechanical factors at the workplace, such as forceful gripping, a deviated wrist angle from a neutral position, and vibration, are often associated with the incidence of CTS (Bao et al., 2015; Harris-Adamson et al., 2015; You et al., 2014). In addition, work organizational and technology factors, such as working hours and duration of computer use per day, are risk factors associated with work-related CTS (Bao et al., 2016; Petit et al., 2015). Therefore, the elements of computer work, such as workstation design, input devices, and working hours, may contribute to a high risk of musculoskeletal disorders among computer users (Gerr et al., 2004; Marcus et al., 2002).

The upper extremity posture, force applied to the input device, and repetitiveness and duration of the task involving the use computer input devices, such as a keyboard and mouse, could contribute to musculoskeletal discomfort among computer users (Cook, Burgess-Limerick, & Papalia, 2004; Dennerlein & Johnson, 2006; Gerr et al., 2006). The common wrist postures during keyboard and mouse use are extension, ulnar deviation, and pronation (Baker et al., 2007; Baker, Cham, Cidboy, Cook, & Redfern, 2007). Several studies have reported that changes in wrist posture, finger movement, and contact stress can lead to an increase in carpal tunnel pressure (Keir, Bach, & Rempel, 1998; Keir et al., 1997; Keir & Wells, 1999; Rempel, Keir, Smutz, & Hargens, 1997; Rempel, Bach, Gordon, & So, 1998). On the other hand, wrist and/or finger movements cause the cross-sectional area of the median nerve to become small at the carpal tunnel region (Loh & Muraki, 2015; Loh et al., 2015; Lopes et al., 2011; Wang et al., 2014).

Previous laboratory studies have reported that computer keyboard typing causes acute swelling of the median nerve and that an ulnar deviated wrist during keyboard typing may be a predictor of median nerve changes (Toosi, Impink, Baker, & Boninger, 2011; Toosi, Hogaboom, Oyster, & Boninger, 2015). However, these studies did not examine the effects of keyboard slope during the computer-typing task on wrist angle changes and the influences on median nerve changes. Additionally, the design of the keyboard and its position on the workstation could lead to different wrist postures during keyboard typing (Kotani, Barrero, Lee, & Dennerlein, 2007; Rempel, Barr, Brafman, & Young, 2007). Therefore, the primary objective of the present study was to investigate the effects of continuous typing on median nerve changes at the carpal tunnel region at two different keyboard slopes (0° and 20°). The secondary objective was to investigate the differences in wrist kinematics and wrist anthropometric changes when typing at the two different keyboard slopes.

4.2 Materials and Methods

4.2.1 Participants

A convenience sampling method was used to recruit participants in this study. Fifteen right-handed healthy young men (Table 4.1) without known upper limb musculoskeletal disorders were recruited. The handedness of the participants was determined using the Edinburgh Handedness Inventory (Oldfield, 1971). The participants provided written informed consent, and this study was approved by the Ethics Committee of the Faculty of Design, Kyushu University (Approval number 141).

Table 4.1 Characteristics of the participants (n = 15).

	Mean ± S.D.
Age (years)	24.8 ± 2.3
Height (cm)	173.1 ± 4.8
Weight (kg)	69.9 ± 9.6
BMI (kg/m^2)	23.4 ± 3.3
Day span (days) between	
Condition I – II	5.3 ± 2.7
Condition II – III	4.1 ± 2.0
Condition I – III	9.4 ± 4.2

4.2.2 Experimental Protocol

Participants were required to participate in the following three conditions: control, typing I, and typing II. A randomized sequence of the conditions was assigned to the participants. Additionally, the participants were instructed not to perform exercises or weight training involving forceful and repetitive grasping and/or gripping one day prior to participating in the conditions.

Anthropometric measurements for a seated computer workstation were performed prior to participation in the conditions. The participants used a height-adjustable table and chair for all the conditions. First, the chair height was adjusted to allow 90° knee flexion with the feet rested on the floor. Then, the table height was adjusted such that it was aligned to the participant's seated elbow height. Lastly, the height of the computer monitor was set at the participant's seated eye level.

In the control condition, the participants were seated at the workstation with the forearms placed on the table while watching an entertainment show on the computer monitor. The participants were instructed to minimize upper limb movements throughout the control condition. In the typing I and II conditions, the participants were required to perform four 30-min computer typing tasks. A 106-key Japanese keyboard with a thickness of 15 mm was used for computer typing. The keyboard slope was set at 0° for the typing I condition, and a custom-made wedge was used to set the keyboard slope at 20° for the typing II condition. The Typing Trainer™ software (Typing Master Finland, Inc., Helsinki, Finland) was used to monitor typing performance and collect data for each participant.

The control and typing conditions included seven and eight time blocks, respectively, with each time block lasting for 30 min. Wrist ultrasound examination and wrist anthropometric measurements were performed at the end of every 30-min time block. In addition, kinematic data of the wrist were recorded at four time blocks (0, 30, 60, and 90 min) in all three conditions. In order to minimize the rest time between time blocks, the ultrasound examination and wrist anthropometric measurements were completed within 8 min. The protocol of each condition and summary of the collected quantitative data are presented in Figure 4.1.

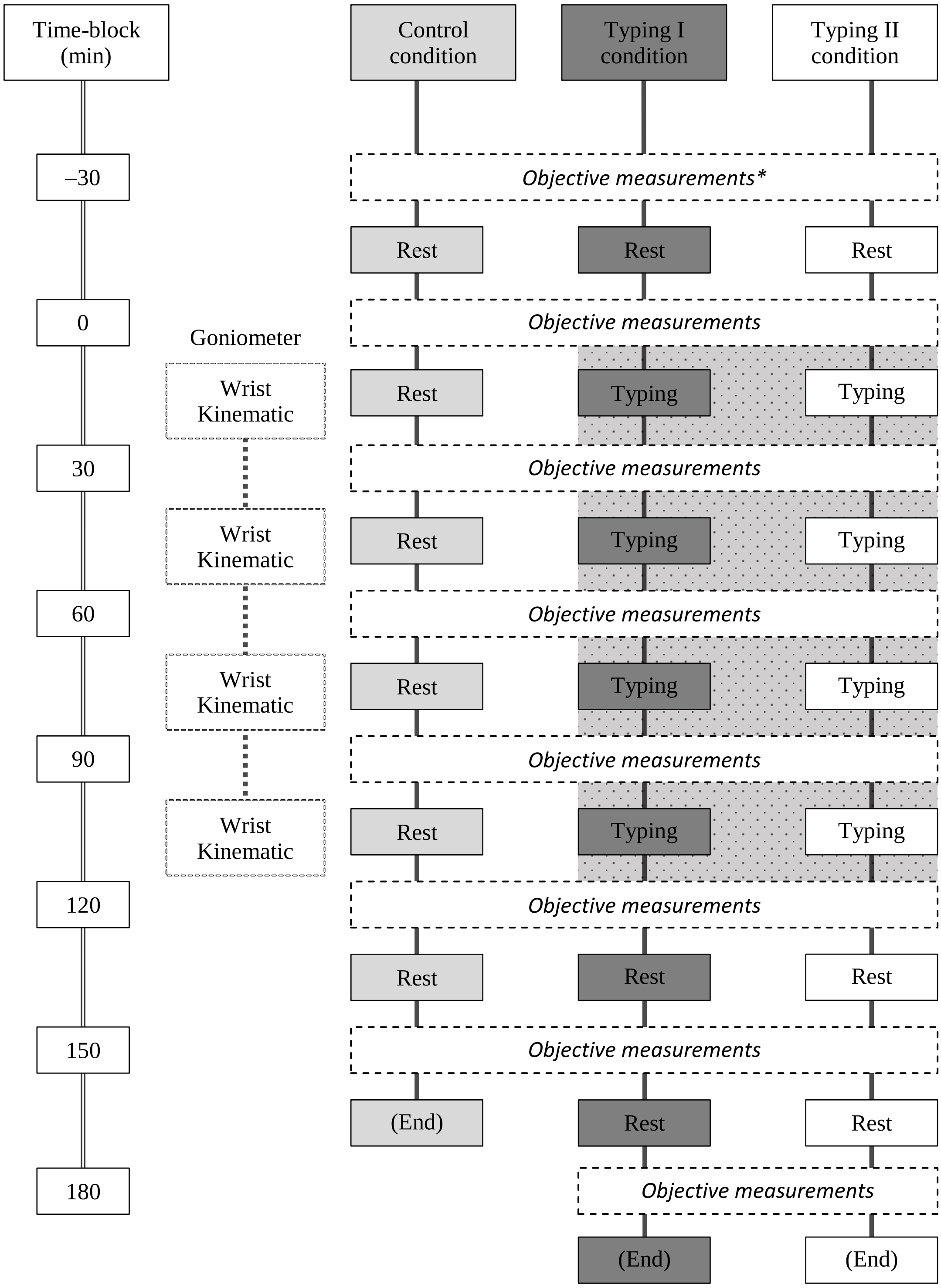

Figure 4.1 Experimental protocol for the control and typing conditions.

**Objective measurements included ultrasound examination and wrist anthropometric measurements.*

4.2.3 Wrist Anthropometric Characteristics and Wrist Kinematic Measurements

The wrist circumference at the distal border of the ulnar styloid level was measured with an anthropometric tape measure (Cescorf Equipamentos para Esporte Ltda, Porto Alegre, Brazil). The wrist width and wrist depth were measured with a sliding caliper at the same level as the wrist circumference measurement. Wrist anthropometric measurement was repeated at each time block.

Bilateral wrist joint movements were recorded with a twin-axis goniometer (Model SG110, Biometrics Ltd, Newport, UK). The distal and proximal end-blocks of the goniometer were attached over the third metacarpal bone and mid-girth of the forearm, respectively. The twin-axis goniometer (SG 110) measured wrist joint movements in two planes (extension/flexion and radial/ulnar deviation). Each goniometer was connected to a wireless goniometer logger and monitored with the Wireless Measurement Application (version 7.11.1) (Sports Sensing Co., Ltd., Fukuoka, Japan) at a 10-Hz sampling rate for both axes. Wrist flexion and ulnar deviation were presented with negative angles. Wrist kinematic measurements were continuously performed for four time blocks (0, 30, 60, and 90 min).

4.2.4 Ultrasound Examination Protocol

Ultrasound images were obtained using the LOGIQ e ultrasound system (GE Healthcare, Milwaukee, WI) with a 12L-RS transducer (imaging frequency bandwidth of 5–13 MHz). A 7.0-mm-thick sonar pad (Nippon BXI Inc., Tokyo, Japan) was used as a coupling agent during the ultrasound examination. The examiner placed the ultrasound transducer gently on the sonar pad to avoid compressive pressure at the wrist during the examination. The forearm was positioned in supination and rested on an arm support on a table, with the elbow at 30° flexion, during the ultrasound examination. The examiner placed the ultrasound transducer parallel to the distal wrist crease to identify the median nerve in the transverse plane, with the proximal border of the pisiform as the anatomical landmark in all conditions. A custom-made L-shaped frame was used to assist the examiner in placing the transducer perpendicular to the wrist. Three images were obtained in a neutral position (0°) for both wrists.

4.2.5 Image Processing and Analysis

The median nerve cross-sectional area (MNCSA) (Fig. 4.2a) was quantified using ImageJ software (National Institutes of Health) (C. A. Schneider et al., 2012). The median nerve was identified as a hyperechoic structure in the transverse plane (Kele, 2012), and then, the MNCSA was quantified using the tracing method (Duncan et al.,

1999) along the hyperechogenic rim. Next, the OpenCV library (version 3.1) (Bradski, 2010) accessed with a python script was used to quantify the longest diameter in the radial-ulnar direction (D1) and longest diameter in the dorsal-palmar direction (D2) on the traced outline of the median nerve using the minimum bounding rectangle method (Fig. 4.2b). The illustrated long and short axes of the rectangle on the image differed slightly from the exact quantified long and short axes, as the rectangle was rounded down from the calculated coordinates (moved towards the top left of the image) to allow it to be drawn on the image. The mean MNCSA, D1, and D2 of three images were calculated at each time block.

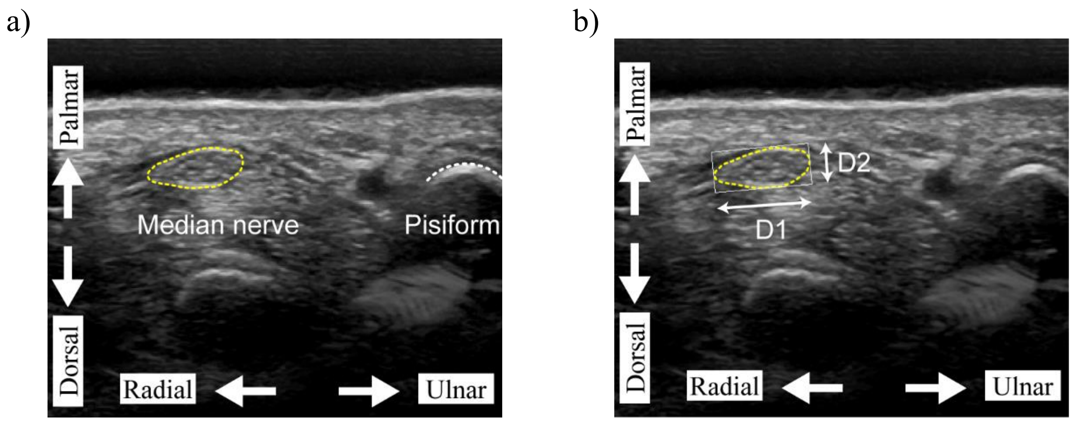

Figure 4.2 Quantification of the (a) median nerve cross-sectional area using the tracing method and (b) median nerve diameter using the minimum bounding rectangle method.

4.2.6 Statistical Analysis

Two-way repeated analysis of variance (3 × 7 factorial design) was performed with the three conditions (control, typing I, and typing II) and seven time blocks (-30, 0, 30, 60, 90, 120 and 150 min) as factors to examine the differences in wrist anthropometric measurements for both wrists. Subsequently, two-way repeated analysis of variance (3 × 4 factorial design) was performed with the three conditions (control, typing I, and typing II) and four time blocks (30, 60, 90, and 120 min) as factors to examine the differences in wrist kinematics for both wrists.

The sample characteristics of the MNCSA were examined using the Shapiro-Wilk's normality test (Razali & Wah, 2011; Shapiro & Wilk, 1965). Next, two-way repeated analysis of variance (3 × 8 factorial design) was performed with the three conditions (control, typing I, and typing II) and eight time blocks (–30, 0, 30, 60, 90, 120, 150, and 180 min) as factors to examine the effects of typing on the MNCSA, D1, and D2. Post-hoc pairwise Bonferroni-corrected comparisons were performed to examine the significant effects between conditions. A post-hoc Dunnett's test was performed to compare the median nerve measurements (MNCSA, D1, and D2) with the time block of 0 min as the control.

A nonparametric Kruskal-Wallis H test was used to examine the differences in typing performance between the typing I and typing II conditions. Subsequently, the Friedman test was performed to examine the repeated measures of typing performances in each condition. All statistical analyses were performed using SPSS version 21.0 software (IBM Corp., Armonk, NY). The significance level was set at $\alpha = 0.05$. All results are presented as mean ± standard deviation.

4.3 Results

4.3.1 Wrist Anthropometric Characteristics

The main effects of condition and time block on the wrist anthropometric measurements were not significant. Wrist circumference, wrist width, and wrist depth remained similar across all the time blocks in the three conditions. The measurements in the control, typing I, and typing II conditions are summarized in Tables 4.2, 4.3, and 4.4, respectively.

Table 4.2 Wrist anthropometric measurements in the control condition (n = 15).

Measurement (mm)	Time (min)						
	–30	0	30	60	90	120	150
Right wrist							
Wrist circumference	165.5 ± 7.8	165.5 ± 7.8	165.5 ± 7.8	165.3 ± 7.6	165.1 ± 7.8	165.0 ± 7.9	165.0 ± 7.9
Wrist width	58.1 ± 3.5	58.1 ± 3.4	57.9 ± 3.5	57.8 ± 3.6	57.8 ± 3.6	57.7 ± 3.6	57.7 ± 3.5
Wrist depth	41.9 ± 3.5	42.0 ± 3.6	41.6 ± 3.4	41.7 ± 3.5	41.5 ± 3.5	41.8 ± 3.4	41.6 ± 3.4
Left Wrist							
Wrist circumference	163.9 ± 7.5	163.9 ± 7.4	163.9 ± 7.6	164.1 ± 7.5	164.0 ± 7.5	163.9 ± 7.3	163.9 ± 7.4
Wrist width	57.5 ± 3.4	57.5 ± 3.3	57.5 ± 3.3	57.4 ± 3.5	57.3 ± 3.2	57.3 ± 3.4	57.3 ± 3.3
Wrist depth	40.9 ± 2.8	41.2 ± 2.8	40.8 ± 3.0	40.7 ± 2.8	41.0 ± 3.0	41.1 ± 2.9	40.9 ± 3.0

Table 4.3 Wrist anthropometric measurements in the Typing I condition (n = 15).

Measurement (mm)	Time (min)						
	–30	0	30	60	90	120	150
Right wrist							
Wrist circumference	165.3 ± 7.9	165.2 ± 8.0	165.3 ± 8.0	165.1 ± 8.0	165.1 ± 8.2	164.8 ± 8.2	164.9 ± 8.1
Wrist width	57.7 ± 3.2	57.8 ± 3.2	57.7 ± 3.3	57.6 ± 3.2	57.7 ± 3.2	57.3 ± 3.5	57.4 ± 3.2
Wrist depth	41.8 ± 3.7	41.8 ± 3.5	41.8 ± 3.4	41.5 ± 3.4	41.5 ± 3.6	41.5 ± 3.5	41.5 ± 3.5
Left Wrist							
Wrist circumference	163.9 ± 7.7	164.0 ± 7.8	164.1 ± 7.7	163.9 ± 7.7	163.9 ± 7.9	164.3 ± 7.7	164.1 ± 7.5
Wrist width	57.1 ± 3.5	57.1 ± 3.5	57.0 ± 3.4	57.0 ± 3.2	57.0 ± 3.2	57.1 ± 3.2	57.0 ± 3.3
Wrist depth	41.1 ± 2.9	41.3 ± 3.0	40.9 ± 2.7	40.8 ± 2.8	40.7 ± 2.7	40.7 ± 2.5	40.8 ± 2.5

Table 4.4 Wrist anthropometric measurements in the Typing II condition (n = 15).

Measurement (mm)	Time (min)						
	–30	0	30	60	90	120	150
Right wrist							
Wrist circumference	165.7 ± 8.0	165.8 ± 8.0	165.7 ± 8.3	165.7 ± 8.1	165.5 ± 8.2	165.5 ± 8.3	165.4 ± 8.3
Wrist width	57.7 ± 3.2	57.8 ± 3.4	57.9 ± 3.3	57.7 ± 3.2	57.6 ± 3.6	57.6 ± 3.3	57.6 ± 3.3
Wrist depth	42.1 ± 3.2	42.1 ± 3.3	42.1 ± 3.0	41.9 ± 3.2	41.8 ± 3.4	41.9 ± 3.4	41.9 ± 3.5
Left Wrist							
Wrist circumference	164.6 ± 8.0	164.6 ± 8.1	164.5 ± 8.1	164.6 ± 8.0	164.6 ± 8.1	164.3 ± 8.1	164.3 ± 7.9
Wrist width	57.2 ± 3.2	57.1 ± 3.3	57.3 ± 3.3	57.1 ± 3.2	57.2 ± 3.6	57.1 ± 3.7	57.1 ± 3.6
Wrist depth	41.3 ± 3.4	41.3 ± 3.3	41.3 ± 2.7	40.9 ± 3.1	41.3 ± 3.3	41.3 ± 3.7	41.3 ± 3.4

4.3.2 Wrist Kinematic Measurements

The mean wrist flexion-extension and radial-ulnar deviation angles are summarized in Table 4.5. The main effect of condition on the changes in wrist flexion-extension was significant ($p < 0.01$). The wrist extension was significantly higher in both the typing I and typing II conditions than in the control condition for both wrists ($p < 0.05$) (Fig. 4.3). Furthermore, the wrist extension of only the right wrist was significantly higher in the typing II condition than in the typing I condition ($p < 0.05$). The main effect of time block on the angle changes of wrist flexion-extension was not significant.

The main effect of condition on the wrist radial-ulnar deviation was significant in all conditions ($p < 0.05$). The wrist ulnar deviation was significantly higher in both the typing I and typing II conditions than in the control condition for both hands ($p < 0.05$) (Fig. 4.3). However, there was no significant difference in the wrist radial-ulnar deviation between the typing I and typing II conditions. Similar to wrist flexion-extension movements, the main effect of time block on the changes in wrist radial-ulnar deviation was not significant.

Table 4.5 Mean wrist angles in the control, typing I, and typing II conditions.

Motion Plane	Wrist	Condition		
		Control	Typing I	Typing II
Extension-Flexion (°)	Right	0.3 ± 1.4	15.9 ± 0.6	20.0 ± 0.3
	Left	– 0.5 ± 1.7	15.1 ± 0.7	17.6 ± 0.5
Radial-Ulnar Deviation (°)	Right	– 1.9 ± 0.6	– 12.7 ± 0.4	– 11.7 ± 0.4
	Left	– 3.3 ± 0.8	– 17.0 ± 1.4	– 15.1 ± 0.3

Wrist flexion and ulnar deviation are presented with negative angles.

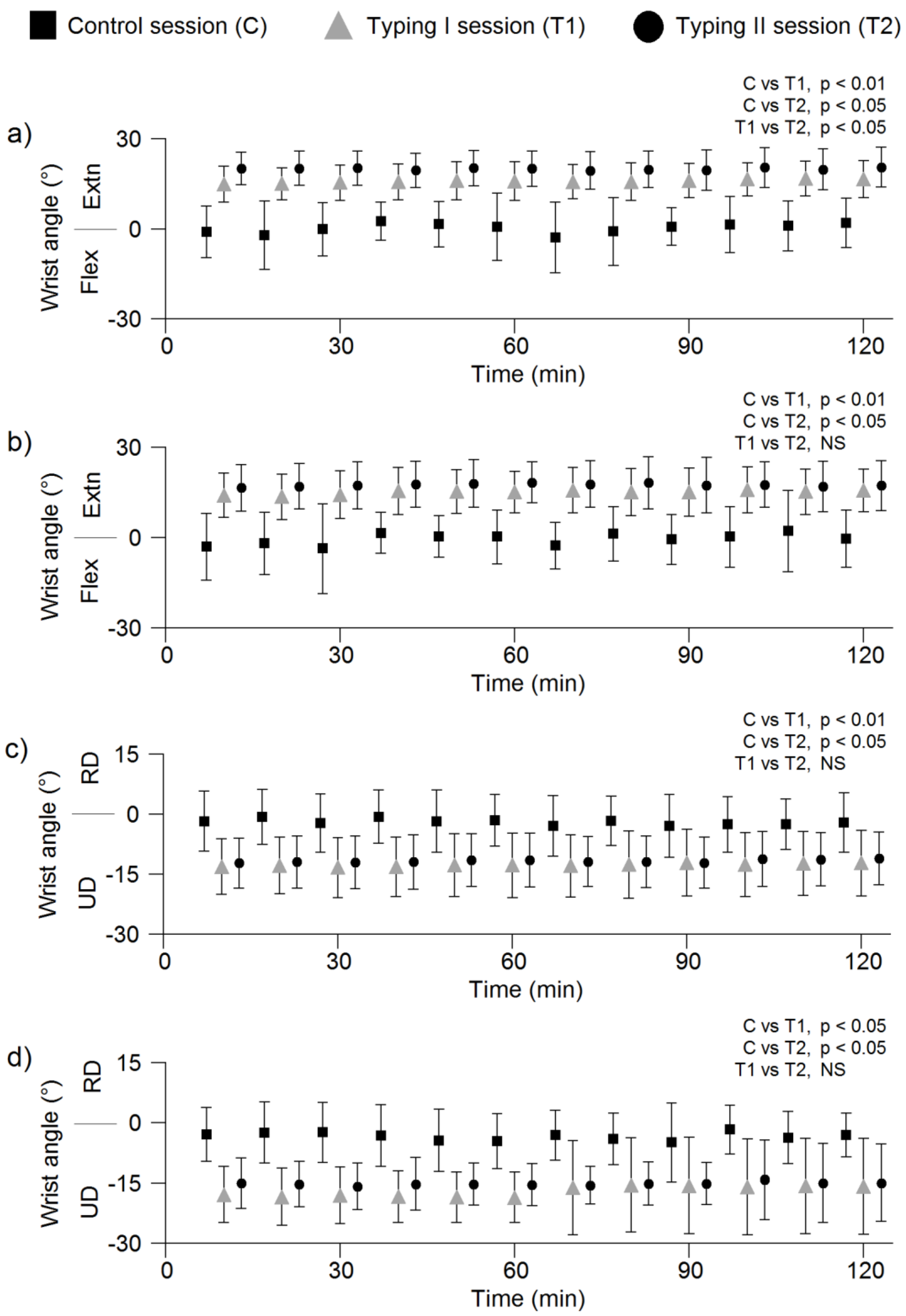

Figure 4.3 Wrist kinematic changes in the three conditions.

(a), (c): right wrist; (b), (d): left wrist. Flex: flexion, Extn: extension; RD: radial deviation; UD: ulnar deviation. The mean wrist angle is presented at 10-min intervals.

4.3.3 Sample Characteristics

Normality tests of the median nerve at the time block of 0 min was conducted in all conditions. The Shapiro-Wilk test ($p > 0.05$) and visual inspection of histograms, normal Q-Q plots, and box plots indicated that the MNCSAs of both hands at the time block of 0 min were approximately normally distributed and slightly skewed and kurtotic in all the three conditions (Table 4.6) (Doane & Seward, 2011; Razali & Wah, 2011; Shapiro & Wilk, 1965).

Table 4.6 Normality test for the median nerve cross-sectional area (n = 15).

Condition	Wrist	Skewness (M ± SE)	Kurtosis (M ± SE)	Shapiro-Wilk Test (p value)
Control	Right	0.018 ± 0.580	–1.481 ± 1.121	0.171
	Left	–0.138 ± 0.580	–0.888 ± 1.121	0.745
Typing I	Right	0.065 ± 0.580	–1.176 ± 1.121	0.471
	Left	0.061 ± 0.580	–0.384 ± 1.121	0.982
Typing II	Right	0.003 ± 0.580	–1.084 ± 1.121	0.493
	Left	0.077 ± 0.580	–1.413 ± 1.121	0.339

M: mean; SE: standard error

4.3.4 Median Nerve Cross-sectional Area Changes in the Control, Typing I, and Typing II Conditions

The main effect of time block on the MNCSA changes was not significant in the control condition. On the other hand, the main effects of condition and time block on the MNCSA changes were significant in both the typing I and typing II conditions ($p < 0.01$). However, the effect of the interaction between condition and time block on the MNCSA changes was not significant. No significant differences were noted in the baseline measurements of the MNCSA (time blocks: -30 and 0 min) in all the three conditions. The MNCSA significantly increased in both the typing I and typing II conditions after the typing task (time blocks: 30, 60, 90, and 120 min) than before the typing task (time block: 0 min) (Fig. 4.4). The MNCSA significantly decreased in the recovery phase (time blocks: 150 and 180 min) after the typing task. Generally, the MNCSA was larger in the typing II condition than in the typing I condition. However, the MNCSA was significantly larger in the typing II condition than in the typing I condition only for the right wrist.

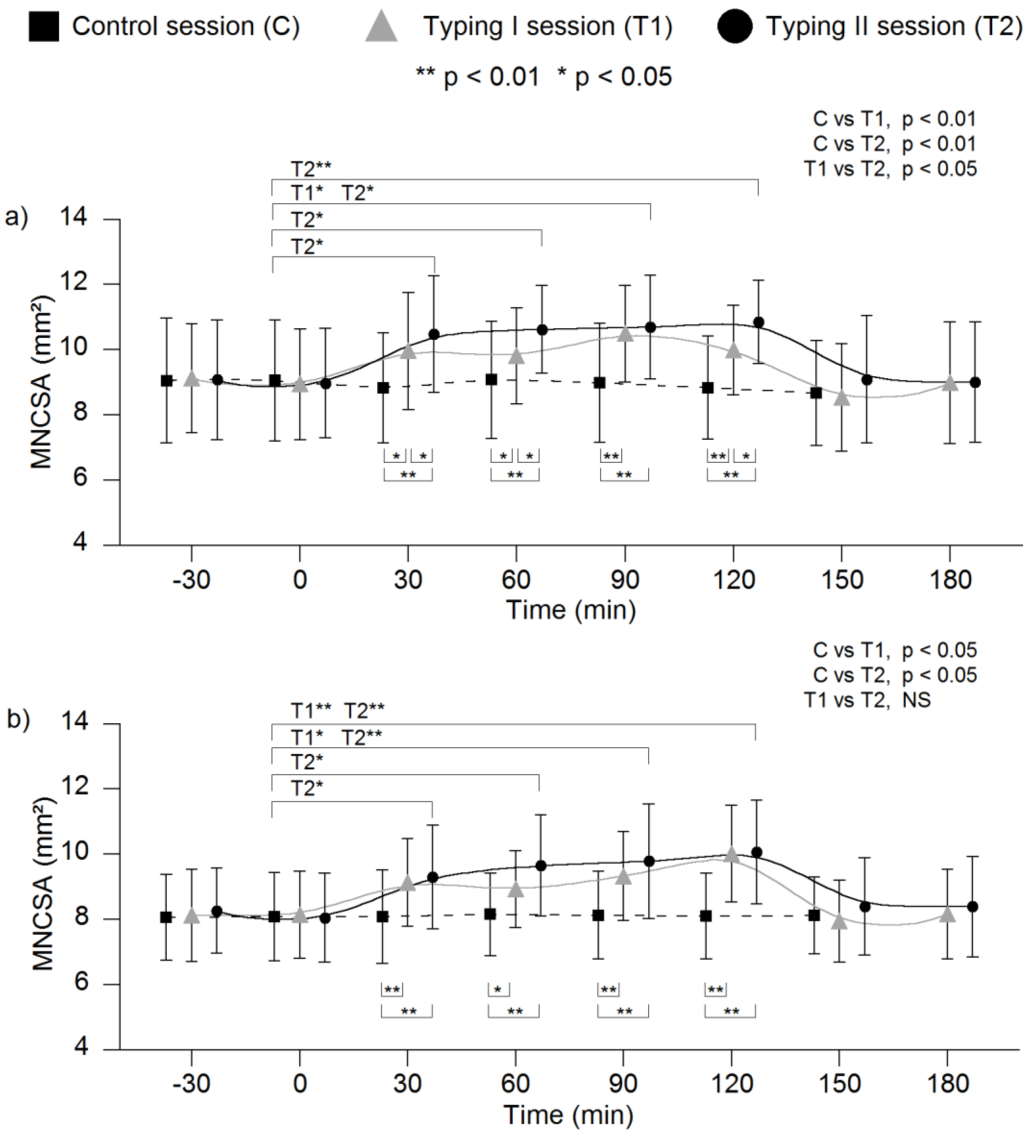

Figure 4.4 Median nerve cross-sectional area (MNCSA) changes in all the conditions.

(a) right wrist; (b) left wrist.

4.3.5 *Median Nerve Diameter Changes in the Control, Typing I, and Typing II Conditions*

Similar to the MNCSA, the main effect of time block on the median nerve diameter was significant in both the typing I and typing II conditions ($p < 0.05$). However, Dunnett's test indicated that the main effect of condition on only the D2 changes was significant in both the typing I and typing II conditions ($p < 0.05$) (Fig. 4.5). In addition, the effect of the interaction between condition and time block on the D1 and D2 changes was not significant. The D2 values at the time blocks of 60 and 90 min were larger in the typing I and typing II conditions than in the control condition.

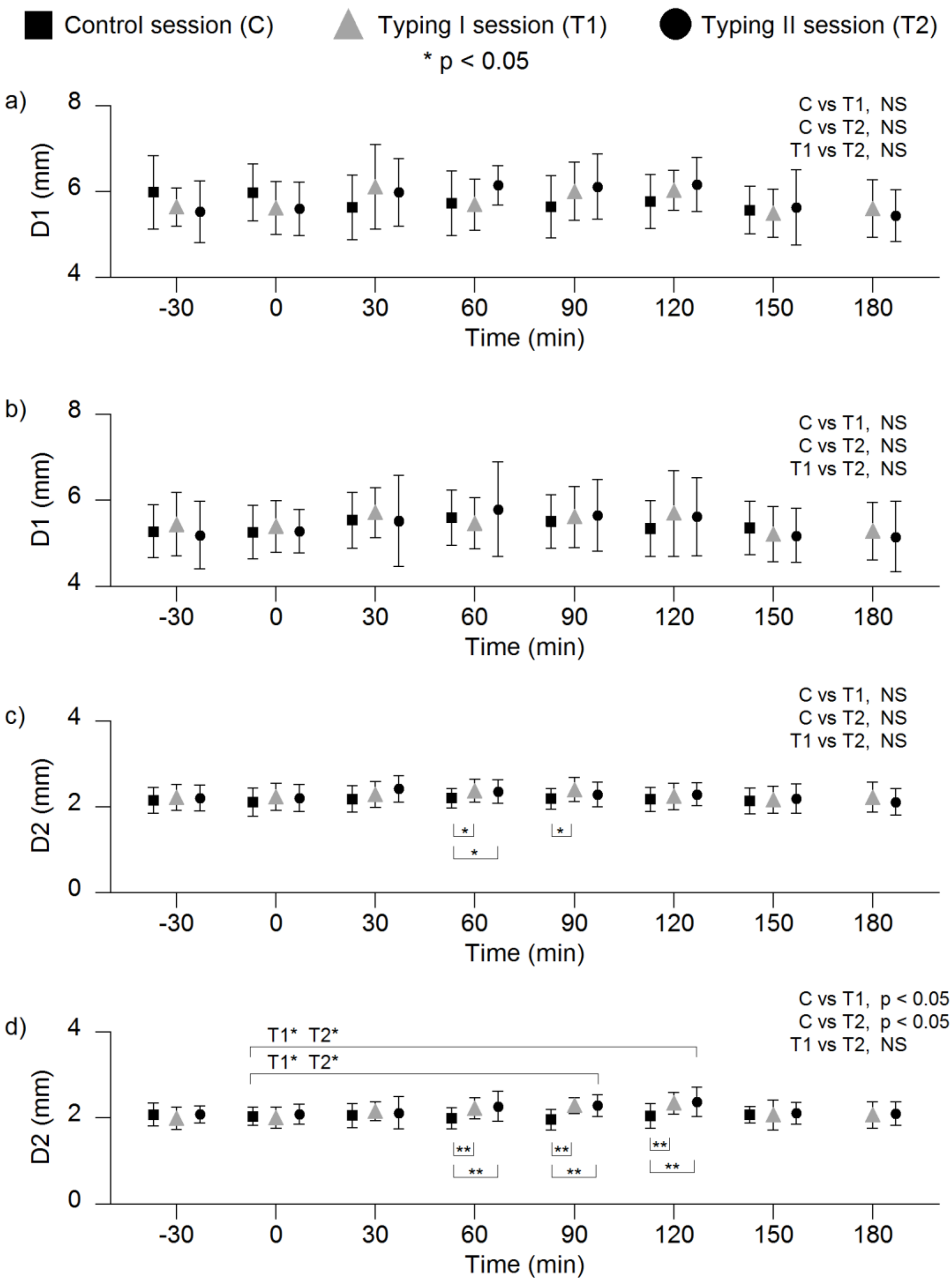

Figure 4.5 Median nerve diameter (D1 and D2) changes in all the conditions.

(a), (c) right wrist; (b), (d) left wrist.

4.3.6 *Typing Performances*

Table 4.7 summarizes the typing performances in both the typing I and typing II conditions. The Kruskal-Wallis H test indicated no significant differences in typing performances (words per minute [WPM], gross stroke, and accuracy) between the typing I and typing II conditions. The typing performances between time blocks were not significant, except for the gross stroke in the typing I condition ($p < 0.01$) (Table 4.8).

Table 4.7 Summary of typing performances in the typing I and II conditions (n = 15).

Condition	Performance	Time (min)			
		30	60	90	120
Typing I	WPM	24.9 ± 12.0	25.3 ± 10.2	26.5 ± 10.2	26.2 ± 11.0
	Gross stroke	3806 ± 1808	3816 ± 1584	4048 ± 1514	4068 ± 1696
	Accuracy (%)	92.9 ± 4.2	94.7 ± 2.2	94.8 ± 2.5	94.9 ± 1.6
Typing II	WPM	27.3 ± 11.4	27.5 ± 11.1	27.5 ± 11.4	27.5 ± 10.2
	Gross stroke	4174 ± 1704	4177 ± 1672	4201 ± 1721	4186 ± 1549
	Accuracy (%)	94.4 ± 2.3	94.5 ± 2.4	95.2 ± 1.3	94.8 ± 1.9

WPM: words per minute

Table 4.8 Summary of the Friedman test results for typing performance (n = 15, df = 3).

Performance	Condition	Mean rank at each time (min)				Chi- Square	p-value
		30	60	90	120		
WPM	Typing I	2.00	2.20	3.10	2.70	7.24	0.065
	Typing II	2.27	2.40	2.63	2.70	1.29	0.732
Gross stroke	Typing I	1.80	2.07	3.13	3.00	11.96	0.008
	Typing II	2.40	2.33	2.53	2.73	0.84	0.840
Accuracy (%)	Typing I	1.83	2.57	2.93	2.67	6.74	0.081
	Typing II	2.20	2.23	3.07	2.50	5.71	0.127

4.4 Discussion

4.4.1 Wrist Anthropometric Characteristics

Asymmetrical wrist kinematics and wrist postures are commonly seen among computer users while typing. In the present study, wrist anthropometric characteristics, such as circumference, width, and depth measured in the three conditions remained almost unchanged before and after continuous typing (Tables 4.2–4.4). These results suggest that continuous keyboard typing and differences in keyboard slope do not cause acute changes to wrist anthropometric characteristics.

4.4.2 Impact of Keyboard Typing on the Median Nerve Cross-sectional Area

In the present study, the MNCSAs of both wrists were significantly higher in the typing conditions than in the control condition (Fig. 4.4). The increases in the MNCSA after typing for 30 min could be due to compression stress at the median nerve secondary to the wrist extension posture, as well as the finger flexor tendons gliding during typing. According to previous studies, single finger and multiple finger flexion movements, and task duration are known to cause a high shear force between tendons (Kociolek et al., 2015; Tat et al., 2013; Yoshii, Zhao et al., 2009). Therefore, repetitive finger flexion movements during keyboard typing could lead to an increase in the MNCSA secondary to subsynovial connective tissue swelling from friction between the finger flexor tendons and the median nerve.

The underlying factors that contribute to acute swelling of the peripheral nerve after physical work remain unclear. Generally, physical work has been shown to cause inflammation of the neural tissues and changes in the cross-sectional area of the peripheral nerve (Barbe et al., 2013; Roll, Evans, Volz, & Sommerich, 2013). Moreover, studies have demonstrated distinguishable mechanical properties and shear movements of the sheath and the core of peripheral nerve during the application of pullout force (Georgeu et al., 2005; Tillett, Afoke, Hall, Brown, & Phillips, 2004). Therefore, repetitive wrist and finger joint movements could increase the neural dynamic gliding properties and the transverse contraction stress on the median nerve. Therefore, both extra-neural factors, such as shear strain and compressive stress from subsynovial connective tissues and finger flexor tendons, and intra-neutral movements, such as fascicle friction within the epineurium, might contribute to the swelling of the median nerve (Fig. 4.4) after continuous keyboard typing.

The median nerve measurements between typing with the keyboard at a 0° slope and a 20° slope were compared. The MNCSA was larger when participants typed at a 20° slope than at a 0° slope for both wrists (Fig. 4.4). Additionally, the wrist extension angle was greater when participants typed at a 20° slope than at a 0° slope (Table 4.5). The carpal tunnel volume reduces as the wrist deviates into an extension posture (Mogk & Keir, 2008). Consequently, the shear strain of the subsynovial connective tissue is known to increase as the wrist deviates from a neutral position to extension and flexion (Yoshii et al., 2008). Therefore, typing with a high wrist extension angle may potentially result in high biomechanical stress at the median nerve owing to a high shear strain at the subsynovial tissues between the finger flexor tendons within the carpal tunnel. A previous study suggested that a high wrist ulnar deviation during typing could lead to a high swelling ratio of the median nerve (Toosi et al., 2015). However, the ulnar deviation angles in both typing conditions were approximately –12° and –16° for the right and left wrists, respectively. Therefore, high wrist extension during typing at a 20° slope may lead to a greater change in the MNCSA than that observed when typing at a 0° slope.

Notably, the MNCSA was consistently larger at each typing time block until the end of the typing task than at baseline (time block: 0 min). Subsequently, the MNCSA recovered to the baseline level after 30 min of rest (time block: 150 min) and remained the same after 60 min of rest (time block: 180 min) (Fig. 4.4). Although the typing tasks in this study were 1 hour longer than the tasks in previous laboratory studies (Toosi et al., 2011; Toosi et al., 2015), the effect of rest on the median nerve after continuous keyboard typing observed in this study is in agreement with the findings of previous studies. Therefore, rest after continuous keyboard typing is important to allow recovery of the swollen median nerve.

4.4.3 Impact of Keyboard Typing on the Median Nerve Diameter

Previous studies explained the morphologic adaptability of the median nerve to extra-neural stress by showing a decrease in the MNCSA and changes in the median nerve diameter at different wrist and finger postures (Loh et al., 2015; Loh & Muraki, 2015; Loh, Nakashima, & Muraki, 2016). Therefore, the irregular shape of the median nerve is influence by compression stress from surrounding finger flexor tendons within the carpal tunnel. The changes in the MNCSA in the typing I and typing II conditions may suggest an observable proportionate change in the median nerve diameter over typing time. The changes in D1 were inconclusive between the typing I and typing II conditions at different time blocks. In contrast, the D2 values of the left hand were significantly larger at the time blocks of 90 and 120 min than at baseline (time block: 0 min).

Originally, the median nerve diameter was postulated to increase corresponding to the changes in the MNCSA. However, an increase in the MNCSA after keyboard typing did not affect the change in the median nerve diameter (Fig. 4.5). These findings may suggest a limited capacity for the median nerve to expand in the longitudinal and vertical directions (Fig. 4.2b) in response to intra-neural edema. Therefore, an increase in the MNCSA with an unchanged median nerve diameter after keyboard typing may indicate an elevation of the intra-neural pressure within the median nerve at the carpal tunnel region. Studies have suggested that the endoneurial fluid pressure increases rapidly and persists after exposure to extra-neural stress (Lundborg et al., 1987; Lundborg & Dahlin, 1992; Lundborg & Dahlin, 1996; Mackinnon, 2002; Rempel, Dahlin, & Lundborg, 1999). Consequently, compressive and shear stresses resulting from repetitive wrist and finger movements may potentially cause edema at the median nerve.

The present study had some limitations. First, the participants in this study had a typing speed of approximately 27 WPM, which is lower than the average typing speed of 36–55 WPM (Povlsen, 2011; Toosi et al., 2011). A slow typing speed may reduce the impact of biomechanical stress on the median nerve and consequently affect the median nerve measurements. Second, the contact force of the palmar wrist on the table was not measured in the control and typing conditions. External contact stress at the wrist may affect the carpal tunnel volume and carpal tunnel pressure. Third, individual differences with regard to the fingertip force applied during keyboard typing may influence the changes in the median nerve.

4.5 Conclusion

This study demonstrated changes in the median nerve after continuous keyboard typing. Changes in the median nerve were greater during typing using a keyboard tilted at 20° than during typing using a keyboard tilted at 0°. The observed results provide a better understanding of the impact of continuous keyboard typing on the median nerve. Additionally, a 30-min rest time is sufficient to enable the median nerve to return to the baseline measurement. Furthermore, placement of the keyboard in a neutral position (0°) could prevent a high wrist extension angle during keyboard typing, and it may reduce acute changes in the median nerve. The findings may benefit and improve ergonomic interventions for the prevention of keyboard-related CTS. Further studies are needed to investigate the effects of various factors, such as wrist posture during daily working hours and duration of computer use, on median nerve changes.

4.6 Appendix

4.6.1 Appendix 4.1 Condition sequences for all participant.

Participant	Condition sequence*
1	B A C
2	C B A
3	B A C
4	B C A
5	B C A
6	B A C
7	A C B
8	B A C
9	B C A
10	C B A
11	A B C
12	C A B
13	A C B
14	C A B
15	A B C

* A = control, B = typing I, C = typing II

Chapter 5 General Discussion and Conclusions

5.1 Summary

Multiple factors contribute to work-related CTS such as personal characteristics, biomechanical, psychosocial, and organizational factors. In recent years, several ultrasound studies investigated the impact of biomechanical stresses such as finger flexor tendon gliding and external compression on the deformation of the median nerve in healthy and CTS individuals (Main et al., 2012; Tat et al., 2013; van Doesburg et al., 2012; Yoshii et al., 2009; Yoshii et al., 2013). However, evidence of the present research still remains inconclusive and is unable to address comprehensively the pathophysiology of CTS. Therefore, investigation of morphological changes and biomechanical relationship of the structures within the carpal tunnel is warranted for a wider understanding of CTS development.

Recently, author of this thesis started to investigate the underlying biomechanical stresses arising from wrist postures on the median nerve within the carpal tunnel which relates to CTS prevention (Loh, 2015). Morphological characteristics of the median nerve at different wrist conditions were investigated and discussed. First, active and passive wrist holding do not cause significant changes in the shape of the median nerve at different wrist angles. Additionally, a maximal wrist radial-ulnar deviation in a neutral wrist position, 30° flexion, and 30° extension did not cause further deformation of the median nerve when compared to a neutral, non-radial/ulnar deviated posture. The overall results suggested that wrist flexion-extension is the main factor leading to significant changes in the MNCSA.

Subsequently, detailed examination of the relationship between the wrist posture and deformation of the median nerve was conducted by considering the functional range of motion of the wrist joint in daily work tasks. The MNCSA and the diameter of the median nerve (D1 and D2) in the wrist in different postures including 15°, 30°, and 45° of flexion and extension were analyzed and compared to the neutral wrist (0°) as a control. In general, wrist posture in flexed or extended position caused a significant decrease in the MNCSA. Additionally, wrist flexion and extension caused a significant decrease in D1 and D2 respectively. Notably, a greater flexion or extension angle resulted in a greater deformation of the MNCSA and median nerve diameter. In addition, two studies involving 87 participants (young men, n = 27; young women, n = 26; older men, n = 34) also investigated the differences between handedness, sex, and age group. Based on findings, measurements of the median nerve in the dominant hand are larger than those in the non-dominant hand and measurements among young men are larger than among young women. On the other hand, trends of median nerve deformation are similar in young and elderly men regardless of larger measurements among elderly men. In summary, wrist posture changes impose biomechanical stress on the carpal tunnel and affect behavior of the median nerve.

This thesis was begun to continue the relevant research work done by Loh (2015). The overriding purpose was to suggest and improve existing ergonomics intervention and prevention guidelines for work-related CTS by identifying underlying biomechanical factors of the active wrist and finger movements causing changes in the median nerve. In order to achieve the aims and goals of this study, the morphological characteristics of the median nerve were examined and analyzed using high-resolution ultrasound imaging technique. The studies presented in this thesis were focused on the impact of biomechanical factors such as wrist and finger joints as well as working duration on the median nerve within the carpal tunnel region. The deformation of the median nerve cross-sectional area and median nerve diameter were examined and summarized in each study.

Various joint angles of the metacarpophalangeal joint (MCPJ), proximal interphalangeal joint (PIPJ), and distal interphalangeal joint (DIPJ) in each finger posture cause a change in the MNCSA and median nerve diameter. Additionally, force exertion such as power gripping causes a further reduction of the MNCSA. In conjunction to active finger movements, wrist posture exists as an important influential factor of deformation of the median nerve. For instance, deformation of the median nerve during wrist flexion or extension in each finger posture is higher than that in a neutral wrist. Observed results may help to identify finger movements that contribute to work-related CTS. These findings provide broader perspectives regarding biomechanical stress from active finger tendon gliding on the median nerve.

Keyboard typing task requires high repetitive movements of the wrist and finger joints. Morphological investigation of the median nerve revealed that a 30-minute keyboard typing task can have an acute impact on the median nerve. Subsequently, the wrist kinematics when typing using keyboard of higher tilted slopes results in a greater wrist extension, which could possibly link to higher changes of the median nerve. Overall, these findings further strengthen the understanding of the effects of prolonged keyboard typing, wrist extension angle, and repetitive wrist and finger movements on the median nerve. Table 5.1 summarizes the deformation of the median nerve at different conditions.

Table 5.1 Summary of the median nerve deformation under different conditions.

Conditions	General conclusions
Wrist flexion-extension with active and passive holding. Young men (n = 8)	1. Significant main effect: wrist flexion-extension at both wrists. 2. Nonsignificant main effect: wrist active–passive holding. 3. MNCSA at wrist flexion and extension are significantly smaller compared to neutral wrist. (Loh & Muraki, 2014a; Loh, 2015)
Wrist flexion-extension with maximum wrist radial-ulnar deviation. Young men (n = 8)	1. Significant main effect: wrist flexion-extension at both wrists. 2. Nonsignificant main effect: wrist radial–ulnar deviation. 3. MNCSA at wrist flexion and extension are significantly smaller compared to neutral wrist. (Loh & Muraki, 2014b; Loh, 2015)
Wrist flexion and extension at 15°, 30°, 45°, and neutral at 0° Young men (n = 27) Young women (n = 26) Older men (n = 34)	1. Significant main effects: sex, wrist flexion-extension. **Sex and handedness** 2. MNCSA and D2 of men are significantly larger than those of women. 3. MNCSA, D1, and D2 of the dominant hand are significantly larger than those of the non-dominant hand in both sexes. **MNCSA** 4. MNCSA at wrist flexion and extension are significantly smaller compared to neutral wrist in both sexes. 5. Greater wrist flexion and extension angles lead to higher deformation percentages than in a neutral wrist. **D1 and D2** 6. Wrist flexion causes significant decrease in D1 in both sexes. 7. Wrist extension causes significant decrease in D2 in both sexes. 8. Wrist extension causes significant decrease in D2 in women. 9. Greater wrist flexion and extension angles lead to higher deformation percentages of D1 and D2 in both sexes. **MNCSA, D1, and D2 of older men** 10. MNCSA of older men is larger than that of younger men. 11. Deformation of MNCSA, D1, and D2 are similar to young men. (Loh, 2015; Loh & Muraki, 2015; Loh et al., 2015)

MNCSA: median nerve cross-sectional area; D1: longitudinal diameter; D2: vertical diameter.

Table 5.1 continue next page

Conditions	General conclusions
Finger tendon gliding postures with wrist flexion-extension Young men (n = 25)	1. Significant main effects: finger postures, wrist flexion-extension. **MNCSA** 2. Changes in MCPJ, PIPJ, and DIPJ in different finger postures decreased significantly in comparison to the relaxed finger. 3. Greater wrist flexion and extension angles lead to higher deformation percentages than in a neutral wrist. **D1 and D2** 4. D1 significantly changes in different finger postures. 5. D2 remains almost unchanged in different finger postures. (Chapter 2)
Grip force with wrist flexion-extension Young men and women (n = 29)	1. Significant main effects: grip, wrist flexion-extension. **MNCSA** 2. Unclenched and clenched fists cause significant decrease in MNCSA. 3. Deformation of MNCSA in a clenched fist is highest. 4. Greater wrist flexion and extension angles lead to higher deformation percentages than in a neutral wrist. **D1 and D2** 5. Significant changes at both unclenched and clenched fists. (Chapter 3; Loh et al., 2016)
Continuous keyboard typing with two keyboard slopes Young men (n = 15)	1. Significant main effects: keyboard slope, typing condition, time block. 2. Nonsignificant main effects: wrist anthropometric, typing performances. **Keyboard slope** 3. Keyboard tilted at 20° lead to a higher wrist extension during typing tasks. **MNCSA** 4. Significantly increased after typing tasks. 5. Significantly recovered to baseline after a resting phase. 6. Changes of the MNCSA at 20° keyboard slope are higher than at 0° slope keyboard. **D1 and D2** 7. D1 and D2 remain almost unchanged after typing task. (Chapter 4)

MNCSA: median nerve cross-sectional area; D1: longitudinal diameter; D2: vertical diameter; MCPJ: metacarpophalangeal joint; PIPJ: proximal interphalangeal joint; DIPJ: distal interphalangeal joint

5.2 Recommendations

The following recommendations for CTS prevention, based on the person-environment-occupation model (Law et al., 1996) and biomechanical frame of reference (James, 2003), are proposed. These recommendations (Tables 5.2 and 5.3) intend to offer additional conceptual ideas for workplace ergonomics assessment, work task analysis, and ergonomics intervention in relation to prevention of work-related CTS.

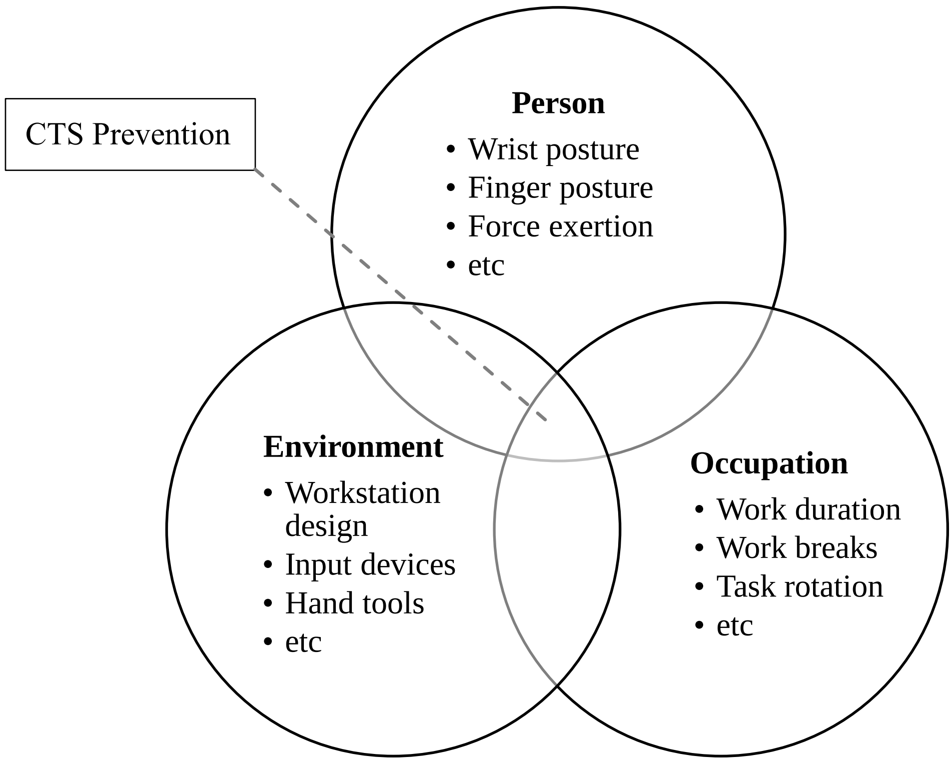

Figure 5.1 Person-Environment-Occupation Model of CTS prevention.

Table 5.2 General recommendations for CTS prevention.

Components	Recommendations
Wrist posture	1. To promote neutral wrist posture in daily work.
	2. To avoid end-range wrist posture in work task and during resting.
	3. To incorporate external support to facilitate and reinforce neutral wrist posture.
Finger posture	1. To avoid repetitive single digit movement in work tasks.
	2. To avoid sustained posture of near full flexion at MCPJ, PIPJ, and DIPJ. E.g. clenched fist or power grip in push-pull work tasks.
	3. To avoid sustained posture of near full flexion at PIPJ and DIPJ. E.g. carrying heavy load in a hook position or full fist postures.
Force exertion	1. To avoid repetitive forceful grip.
	2. To use appropriate tools such as hand tools that allow power grip at lesser flexion of MCPJ, PIPJ, and DIPJ during force exertion.
	3. To use hand gloves that provide stable and firm grasp on the surface when grasping and/or gripping in order to avoid high grip force exertion.
Work duration	1. To avoid continuous work tasks requiring repetitive or static wrist and finger postures.
	2. To include frequent breaks and task rotation in daily work routine.

MCPJ, metacarpophalangeal joint; PIPJ, proximal interphalangeal joint; DIPJ, distal interphalangeal joint.

Table 5.3 Recommendations for CTS prevention with special focus on computer users.

Domains	Components	Recommendations and examples
Person	Wrist posture	1. To promote a neutral wrist position during keyboard typing. 2. Wrist angle during typing should be kept between neutral position and 15° extension, and lesser than wrist 20° ulnar deviation (Keir, Bach, Hudes, & Rempel, 2007; Rempel, Keir, & Bach, 2008) 3. To promote dynamic movements of the elbow and wrist when manipulating a mouse.
	Force exertion	1. To avoid forceful gripping and sustained posture when using a mouse. 2. To avoid continuously clicking mouse with high force as it may increases the shear strain of the subsynovial connective tissue (Tat et al., 2013).
Environment	Workstation design	1. Suitable support that encourages neutral position of the wrist and avoids full pronated forearm. 2. Keyboard and mouse should be placed at the frontal plane within the primary reach zone to avoid awkward wrist and forearm postures.
	Keyboard	1. Non-tilted keyboard (0°) promotes lower wrist extension during typing. 2. Split-keyboard promotes lesser wrist ulnar deviation during typing (Rempel et al., 2007).
Occupation	Work breaks and micropauses	1. To include short break after continuous keyboard typing for 30 to 60 minutes. 2. To promote regular work break at hourly intervals from continuous computer work (Balci & Aghazadeh, 2003). 3. To encourage micropauses (30 to 60 seconds) every 10 minutes (Henning, Jacques, Kissel, Sullivan, & Alteras-Webb, 1997; McLean, Tingley, Scott, & Rickards, 2001).
	Task rotation	1. To encourage rotation of tasks for 15 to 30 minutes in between continuous computer typing at hourly intervals. 2. To prevent highly repetitive movements or sustained postures of the wrist and fingers.

5.3 Limitations and Future Studies

Ultrasound imaging technique is a useful and reliable modality that could be used to investigate morphologic and acute changes of the tissues after physical work exposure. However, ultrasound examination is considered to be an operator- and experience-dependent imaging modality. Placement of the ultrasound transducer could result in a different imaging angle. In this study, a custom-made L-frame was used to assist transducer placement on the wrist where the wrist crease and pisiform were considered to be landmarks. Subsequently, the direct pressure from the transducer could alter the shape of the median nerve. Therefore, a sonar pad was used as a coupling medium and to prevent direct pressure on the carpal tunnel.

Next, the main results of this study were used to analyze morphological characteristics of the median nerve based on still images in designated wrist and finger postures. Further study on the relationship of the median nerve and the surrounding structures is needed to enhance investigation of the CTS pathophysiology. For example, roles of the flexor pollicis longus on the median nerve deformation and the influence of the palmaris longus on the transverse carpal ligament could be investigated. Furthermore, three dimensional study or alternative imaging techniques may be used adjunctively to improve the understanding of dynamic motion of the median nerve and finger flexor tendons within the carpal tunnel.

Overall, this thesis provides evidence related to morphologic adaptability of the median nerve using a well-designed experimental protocol and physical task exposure. However, there are still unanswered questions as well as unidentified relationships between different physical work exposures and the pathophysiology of CTS. Additionally, translation of the findings from this study to ergonomics and clinical practices is important for CTS prevention. Future research involves a longitudinal study of different occupations, which is needed to identify risk factors and develop an early-preventive intervention plan for work-related CTS.

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