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An MRI evaluation of carpal tunnel dimensions in healthy wrists: Implications for carpal tunnel syndrome

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Abstract

Background. Deviated wrist postures and pinch grip use have been linked to the development of carpal tunnel syndrome and are likely related to the size and shape of the carpal tunnel. The purpose of this study was to quantify carpal tunnel dimensions with changes in wrist posture and pinch grip.

Methods. Eight healthy volunteers (4 male, 4 female) underwent magnetic resonance imaging of their dominant wrists under seven conditions which included: 30° wrist extension, neutral and 30° flexion (with and without a 10 N pinch force) and a fist with a neutral wrist. Cross-sectional area of the carpal tunnel and its contents were calculated at 3 mm increments along the length of the tunnel and integrated to calculate volumes. Ratios were calculated between the contents of the tunnel to the tunnel itself for area and volume.

Findings. The use of a correction factor significantly reduced volume and distal carpal tunnel area in flexed and extended wrists. Carpal tunnel areas were largest in neutral and smallest at the distal end with wrist flexion. An extended wrist resulted in the smallest carpal tunnel and content volumes as well as the smallest carpal tunnel content volume to carpal tunnel volume ratios. While men had significantly larger areas and volumes than women for both the carpal tunnel and it contents, there were no differences in ratios between the contents and tunnel size.

Interpretation. A simple correction factor for non-perpendicular magnetic resonance images proved useful in relating volume changes to known pressure changes within the carpal tunnel. More inclusive and detailed evaluation of the carpal tunnel and its contents is required to fully understand mechanisms for median nerve compression in the carpal tunnel.

Keywords: Carpal tunnel syndrome; MRI; Cross-sectional area; Volume; Wrist; Carpal tunnel

1. Introduction

Carpal tunnel syndrome (CTS) is a common peripheral compression neuropathy which has been related to workplace factors including deviated wrist postures, especially when combined with repetitive and forceful use of the hand (Silverstein et al., 1987). These factors have also been related to increased pressure and impingement of the median nerve within the carpal tunnel (Gelberman et al., 1981; Keir et al., 1997). Both carpal tunnel pressure (CTP) and median nerve impingement have been related to the size and shape of the tunnel. While it is clear that CTS involves compression of the median nerve at the wrist, the mechanism by which that compression occurs has yet to be clearly determined.

Trauma to the median nerve has been associated with increased carpal tunnel pressure (Gelberman et al., 1981; Richman et al., 1987; Szabo and Chidgey, 1989). CTS patients typically have higher CTP than controls and several studies suggest a smaller carpal tunnel in patients (Dekel et al., 1980; Horch et al., 1997). The high CTP in patients may be instantaneously reduced by transection of the transverse carpal ligament (Gelberman et al., 1981)

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which enlarges the tunnel (Garcia-Elias et al., 1992; Kato et al., 1994; Okutsu et al., 1989). The link between pressure and carpal tunnel size is intuitive; if the carpal tunnel behaves as a closed compartment, an increase CTP must be concurrent with a decrease in carpal tunnel size and/or an increase in the contents of the carpal tunnel.

The size and shape of the carpal tunnel are dependent on wrist posture. In the neutral wrist, the cross-sectional area of the carpal tunnel (CTA) has typically been reported to be smaller distally (hook of the hamate) than proximally (pisiform) (Dekel et al., 1980; Horch et al., 1997; Merhar et al., 1986; Monagle et al., 1999; Yoshioka et al., 1993). With the wrist extended, the CTA has been found to increase distally but decreased proximally (Horch et al., 1997; Yoshioka et al., 1993); while wrist flexion has been reported to decrease CTA throughout the tunnel (Skie et al., 1990). These changes in CTA cannot fully explain the changes in CTP with wrist posture. CTP is known to increase to a greater extent with wrist extension than flexion, however, CTA has been reported to decrease to a greater extent with flexion. This indicates that carpal tunnel area alone cannot account for the large increase in CTP with wrist extension and supports the suggested impingement mechanism with wrist flexion (Keir et al., 1997).

There have been very few examinations of carpal tunnel volume and those studies have been limited to neutral wrist postures (Cobb et al., 1992; Pierre-Jerome et al., 1997a,b; Richman et al., 1987). There is strong evidence that structures within the carpal tunnel may be responsible for changes in pressure associated with wrist deviation (Cobb et al., 1992; Keir and Bach, 2000). These structures include the lumbrical muscles (Cobb et al., 1994, 1995; Yii and Elliot, 1994), the finger flexor muscles (Holtzhausen et al., 1998; Keir and Bach, 2000), their tendons and synovial sheaths, as well as anomalous growths (Zeiss and Guilliam-Haidet, 1996). The relationship between the size of the carpal tunnel and its contents has been suggested as an anatomic basis for carpal tunnel syndrome (Cobb et al., 1992).

A detailed magnetic resonance imaging (MRI) analysis of the carpal tunnel is warranted to examine the areas and volume of the carpal tunnel and its contents, as well as their relationships, in neutral and non-neutral postures as it is an important step in determining the mechanisms of median nerve trauma in carpal tunnel syndrome. In addition, previous examinations have found that pinch and tendon forces alter the trajectory of the tendons (Keir and Wells, 1999) and pressures within the tunnel (Keir et al., 1997). Thus, the purpose of this study was to quantify the dimensions of the carpal tunnel as a function of wrist posture and a pinch grip using magnetic resonance imaging.

2. Methods

2.1. Participants

The right (dominant) wrist of 4 male and 4 female volunteers were imaged. Participant anthropometries were measured including height, body mass and hand/wrist dimensions. All volunteers completed an MRI contraindication questionnaire and gave informed written consent prior to participating in the study. This study was approved by the University Human Participants Review Committee.

2.2. Imaging parameters

MRI was performed using a 1.5 T imaging system (General Electric, Milwaukee, WI, USA). High quality soft tissue contrast was achieved with 2-D axial images using T1 fast gradient echo with fat suppression (TR = 51 ms, TE = 3 ms, flip angle = 30°), 10×8 cm field of view (FOV), 256×192 matrix and 10 acquisitions. Scanning time was dependent on the size of the wrist and ranged from 4 to 6.5 min per condition, resulting in six to eleven 3 mm contiguous slices. Coronal scout images were used to identify bony landmarks such as the radial styloid, pisiform and hook of the hamate, as well as to ensure that the reference matrix was set perpendicular to the longitudinal axis of the forearm, starting at the tip of the radial styloid.

2.3. Protocol

Participants laid prone on the MRI gantry with the arm extended above the head and the wrist positioned within a 17.5 cm diameter extremity coil. To minimize fatigue and movement artifact, the upper torso and arm were supported by foam padding. Wrists were imaged in seven different conditions including three postures (30° extension, neutral and 30° flexion) and two loading conditions (no load and a 10 N pulp pinch using the thumb and index finger); in the seventh condition, participants made a "fist", with the fingers loosely held in flexion with tape, in a neutral wrist posture. Each of the three wrist postures was maintained using plexiglass splints taped to the dorsum of the hand and wrist. Pinch force was regulated using a manometer constructed of clear rubber tubing and filled with a coloured solution. Participants pinched an enlarged portion of the tubing between the index finger and thumb until the fluid reached a visible target zone in the tube (~10 N force). To maintain consistent finger postures between conditions, participants held the tube in all trials, but only applied force during the 'loaded' trials. The manometer was calibrated prior to each session with a force gauge (CSD 200, Chattilon, Ametek, Largo, FL, USA).

2.4. MR image analysis

Images were analyzed from the distal aspect of the radial styloid to the proximal aspect of the metacarpals, ensuring that the full length of the tunnel was included. For each slice, the outlines of the carpal tunnel, median nerve and each of the nine finger flexor tendon were traced (Image-J, VI.30, National Institute of Health, USA). The dorsal and palmar borders of the tunnel were defined as the inner border of the palmar and transverse carpal ligaments,

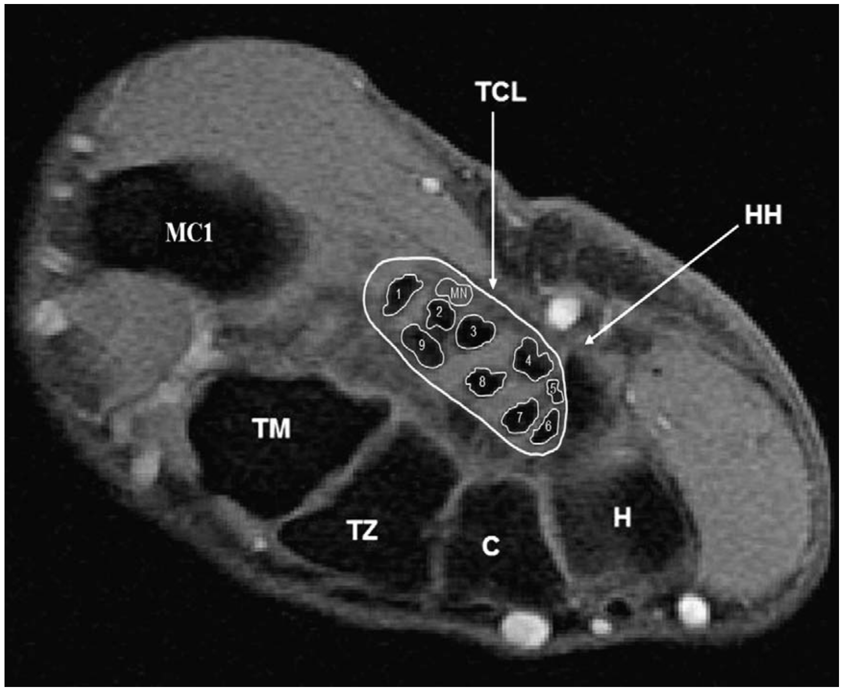

Fig. 1. Axial magnetic resonance image of the carpal tunnel (heavy border) and its contents at the level of the hook of the hamate (HH). Abbreviations: TCL, transverse carpal ligament; MC1, first metacarpal; TM, trapezium; TZ, trapezoid; C, capitate; H, hamate; MN, median nerve; 1, flexor pollicis longus; 2–5, flexor digitorum superficialis; 6–9, flexor digitorum profundus.

respectively. Flexor tendon and median nerve boundaries were identified by abrupt changes in signal intensity at their outer perimeters (Fig. 1).

The traced outlines were used to calculate the cross-sectional area of each structure for each slice, thus defining the carpal tunnel area (CTA) and the carpal tunnel contents area (CTC_A); the latter by summing the individual areas of the median nerve and nine tendons. The volumes of the carpal tunnel (CTV) and the carpal tunnel contents (CTC_V) were calculated by integrating the respective areas along the length of the carpal tunnel, using the trapezoidal method of integration between the 3 mm contiguous slices, keeping the number of slices constant between conditions for each wrist. To calculate the volumes, the end boundaries of the carpal tunnel were defined, proximally, as the most proximal aspect of the pisiform and, distally, as the most distal aspect of the hook of the hamate. Ratios of carpal tunnel contents to carpal tunnel size were calculated for the area at each slice (CTC_A/CTA) and for overall volume (CTC_V/CTV). To further assess the shape of the carpal tunnel and the median nerve, ''flattening ratios'' were calculated by modeling each structure as an ellipse and was defined as the major (radio-ulnar) axis divided by the minor (dorso-palmar) axis.

To address the potential confound of 'parallax error' associated with imaging the carpal tunnel in non-neutral postures, a simple correction factor of 0.8660 ($\cos 30°$) was used to reflect the 30° wrist angle in flexed and extended wrists; this was applied to cross-sectional areas at the hook of the hamate (distal tunnel). For volume calculations, it was assumed that this 30° angle occurred between the level of the pisiform to the hook of the hamate. The 30° angle correction was applied in increments determined by dividing the 30° wrist angle by the number of slices between the pisiform and hook of hamate, resulting in a unique correction factor for each slice.

2.5. Statistical analysis

The effects of gender, posture, level and loading on carpal tunnel, tunnel contents and median nerve CSA and CTC_A/CTA were identified using 2 (gender) × 2 (load) × 3 (posture) × 2 (level) repeated measures ANOVAs. The 2 levels included the pisiform (proximal) and the hook of the hamate (distal). For volume analyses, the same design was used without the level variable. To evaluate the neutral wrist conditions (no load, pinch and fist) separate 3 (load) × 2 (level) mixed ANOVAs were used. All analyses were performed on corrected and non-corrected data, however, unless otherwise stated, the corrected data are presented. To control for any gender effects related to size, all analyses were also performed by normalizing to the neutral unloaded condition. Significance was set at $\alpha = 0.01$ and all significant ANOVA results were further evaluated using contrast analysis.

3. Results

3.1. Cross-sectional area

The correction factor significantly reduced carpal tunnel area (CTA) at the distal end of the carpal tunnel

($F(1,7) = 261.4$, $P = 0.000001$). Without correcting for the angle of the distal slices, the carpal tunnel appeared to be larger at its distal end in extension (hook of hamate) (Table 1). Both the Posture main effect ($F(1,7) = 8.463$, $P = 0.023$) and the Posture × Correction interaction ($F(1,7) = 8.572$, $P = 0.022$) approached but did not attain significance. Note that only the distal carpal tunnel (hook of hamate) areas were corrected and unless otherwise stated, are presented.

3.1.1. Carpal tunnel area (CTA)

Gender had a significant main effect on CTA ($F(1,6) = 14.95$, $P = 0.0083$), with males being larger than females (Fig. 2a vs b). A significant interaction was found

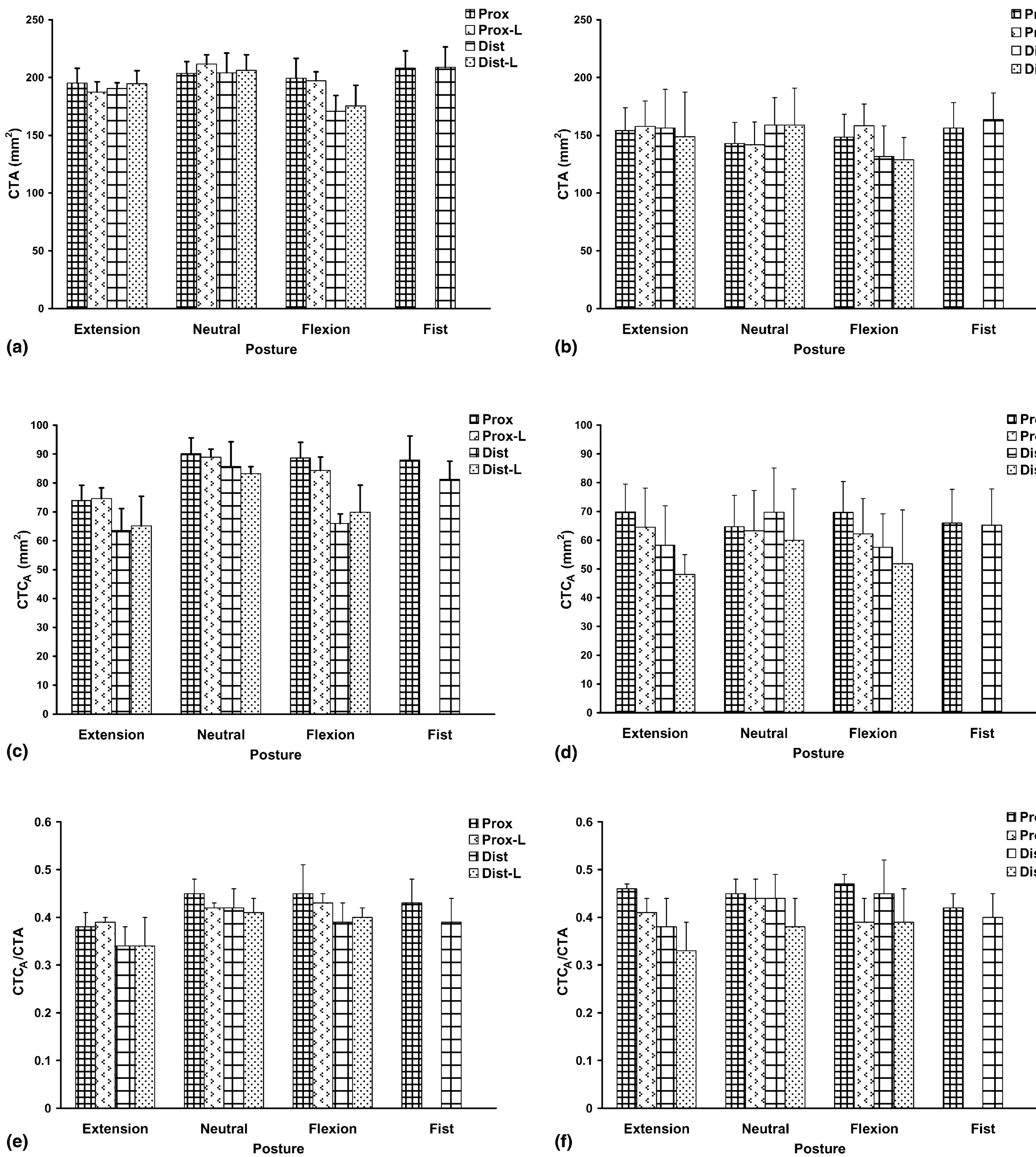

Fig. 2. Mean carpal tunnel cross-sectional area measurements for each wrist posture and loading condition (error bars represent standard deviation), (a) carpal tunnel area (CTA) – men, (b) carpal tunnel area (CTA) – women, (c) carpal tunnel contents area (CTC_A) – men, (d) carpal tunnel contents area (CTC_A) – women, (e) contents to carpal tunnel ratio (CTC_A/CTA) – men, (f) contents to carpal tunnel ratio (CTC_A/CTA) – women. Legend abbreviations: Prox = proximal carpal tunnel, Prox-L = proximal carpal tunnel – loaded, Dist = distal carpal tunnel, Dist-L = distal carpal tunnel – loaded.

between wrist posture and level for carpal tunnel area (CTA) ($F(2,12) = 8.60$, $P = 0.0048$), with the distal CTA being significantly smaller with the wrist flexed than either neutral ($P = 0.001$) or extended ($P = 0.04$) (Fig. 2a). This also resulted in a main effect of Posture ($F(2,12) = 6.91$, $P = 0.01$). At the proximal end of the tunnel (pisiform), the CTA was relatively constant between postures (Fig. 2a and b). In neutral and extended wrists, CTA was similar at both ends of the tunnel, while wrist flexion resulted in a significantly smaller CTA at the hook of the hamate (distal) than at the pisiform (proximal) ($P = 0.0002$) (Fig. 2a and b). When CTA was normalized to the neutral unloaded wrist, the interaction between Level and Posture remained significant and the main effect of Level became significant ($F(1,6) = 28.39$, $P = 0.00178$) due to a large decrease in the area of the distal carpal tunnel with wrist flexion.

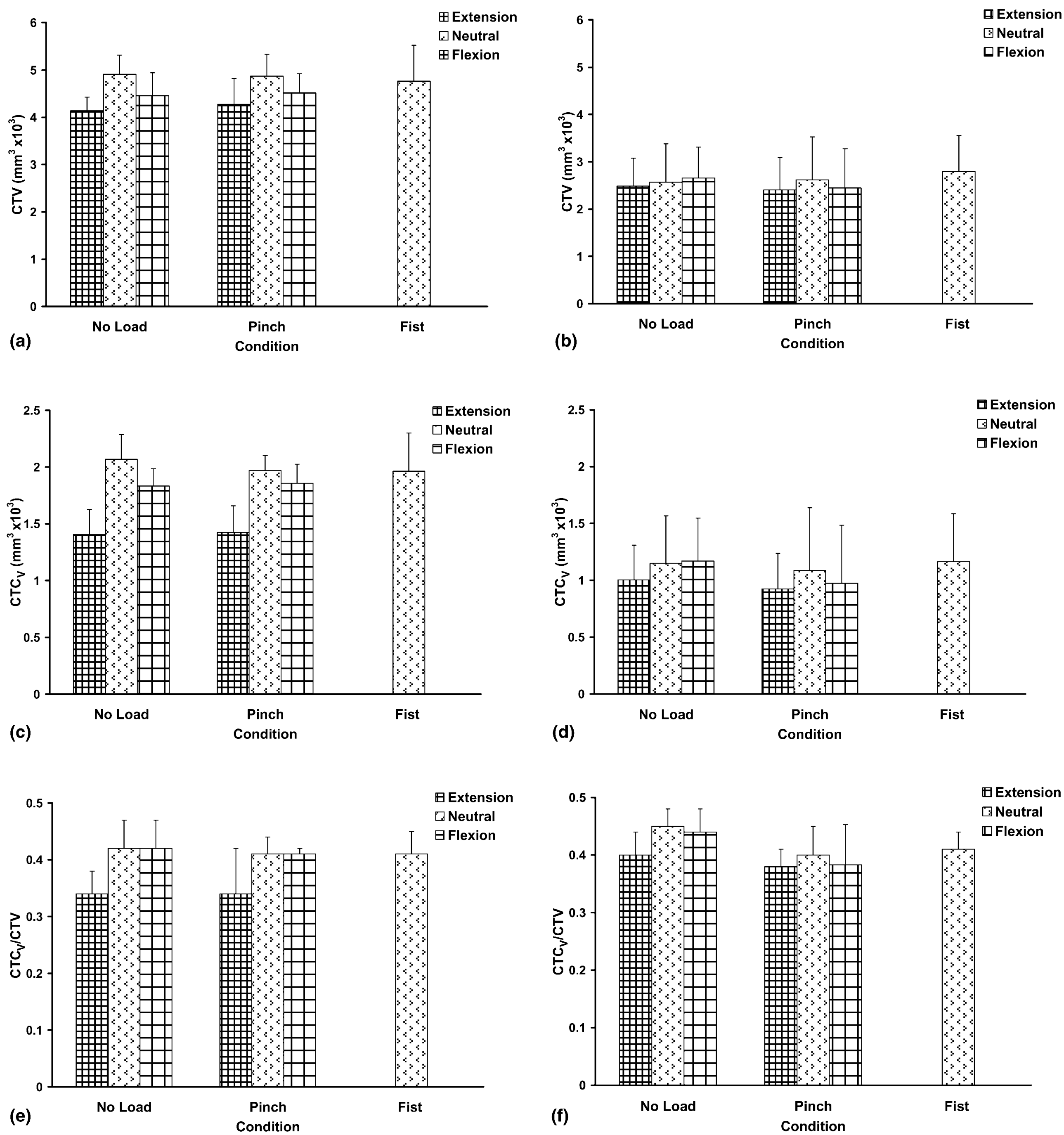

Fig. 3. Mean carpal tunnel volume measurements for each wrist posture and loading condition (error bars represent standard deviation), (a) carpal tunnel volume (CTV) – men, (b) carpal tunnel volume (CTV)– women, (c) carpal tunnel contents volume (CTC_V) – men, (d) carpal tunnel contents volume (CTC_V) – women, (e) contents to carpal tunnel ratio (CTC_V/CTV) – men, (f) contents to carpal tunnel ratio (CTC_V/CTV) – women.

3.1.2. Carpal tunnel contents area (CTC_A)

While gender itself did not have a significant effect on the carpal tunnel contents area (CTC_A), there was a Posture × Gender interaction ($F(2,12) = 124.6$, $P = 0.0012$) as well as main effects of Level ($F(1,6) = 104.4$, $P = 0.00005$) and Posture ($F(2,12) = 33.4$, $P = 0.00001$) (Fig. 2c and d). Normalizing to neutral posture, in addition to the above effects, the Level × Posture interaction became significant ($F(2,12) = 9.47$, $P = 0.0034$) with the contents in proximal tunnel being larger than the distal tunnel except with the wrist in neutral. When normalized to neutral, male CTC_A were greater than females in extension but smaller in neutral. The main effect of Load approached significance ($F(1,6) = 8.57$, $P = 0.026$). ANOVA results of the three neutral posture conditions (pinch, no pinch and fist) indicated that Gender, Level and the Level × Gender interaction all approached significance ($0.018 < P < 0.029$) primarily due to men being significantly smaller at the hook of the hamate than at the pisiform.

3.1.3. Carpal tunnel contents to carpal tunnel area ratio (CTC_A/CTA)

Significant main effects were found for Level ($F(1,6) = 17.44$, $P = 0.0058$) and Posture ($F(2,12) = 24.09$, $P < 0.0001$) (Fig. 2e and f). The 10 N pinch force had a tendency to reduce CTC_A/CTA but the main effect of Load did not attain significance ($F(1,6) = 11.04$, $P = 0.016$). Contrast analyses indicated the ratio to be significantly smaller at the hook of the hamate and the extended wrist resulted in significantly smaller ratios than either flexed ($P < 0.0025$) or neutral ($P < 0.002$) wrists (Fig. 2e and f). Analysis of the three neutral wrist conditions revealed only a near significant main effect for level ($F(1,6) = 7.29$, $P = 0.036$), indicating a smaller CTC_A/CTA at the hook of the hamate (Fig. 2e and f).

3.1.4. Flattening ratios

Due to the pinch grip posture, the shape of the tunnel was not perfectly oval, resulting in poor and varied estimates of flattening ratios. A repeated measures ANOVA revealed a significant interaction between wrist posture and level on the carpal tunnel flattening ratio ($F(2,12) = 35.70$, $P < 0.0001$), with ratios being larger (more elliptical) at the pisiform with the wrist extended ($P < 0.0001$) and neutral ($P = 0.007$) when compared to the distal level, but larger ratios at the hook of the hamate in flexion ($P = 0.04$).

3.2. Volume

3.2.1. Carpal tunnel volume

Application of a continuous correction factor throughout the length of the carpal tunnel resulted in a significant reduction in carpal tunnel volume (CTV) ($F(1,7) = 74.2$, $P = 0.000057$) (Table 2). Women had significantly smaller CTV than men ($F(1,6) = 25.2$, $P = 0.0024$), with a trend towards a posture effect on the corrected volumes ($F(2,12) = 4.39$, $P = 0.037$), with CTV being greatest in neutral followed by flexed, then extended wrist posture (Fig. 3a and b). When normalized to the neutral wrist volume, no effects were significant (all $P > 0.13$).

3.2.2. Carpal tunnel contents volume (CTC_V)

Wrist posture had a significant effect on carpal tunnel content volume ($F(2,12) = 9.81$, $P = 0.003$), with wrist extension having smaller CTC_V than neutral ($P < 0.02$) and flexed ($P = 0.002$) wrists (Fig. 3c and d; Table 2). Women tended to have smaller CTC_V than men, however, the effect of gender was marginally non-significant ($F(1,6) = 12.16$, $P = 0.013$). When normalized to neutral CTC_V, the effect of posture remained significant ($F(2,12) = 7.25$, $P = 0.009$), again with wrist extension having a smaller CTC_V than flexed ($P = 0.005$) and neutral ($P = 0.04$).

3.2.3. Carpal tunnel contents to carpal tunnel volume ratio (CTC_V/CTV)

The only significant effect on the volume ratio between the carpal tunnel and its contents was Posture ($F(2,12) = 15.26$, $P = 0.00051$) due to the CTC_V/CTV being significantly smaller in extension than neutral ($P < 0.001$) and flexion ($P = 0.01$) (Fig. 3e and f). Both Load ($F(1,6) = 6.72$, $P = 0.041$) and Gender × Posture ($F(2,12) = 3.92$, $P = 0.049$) approached significance primarily due to a large decrease in men with wrist extension. Comparison between the three neutral posture conditions (with and without ION pinch, fist) found no significant differences (Fig. 3e and f).

4. Discussion

This comprehensive evaluation of the size of the carpal tunnel, its contents, and their relationship has delivered several key findings. Perhaps the most significant finding of this study was that, while women had smaller carpal tunnel areas and volumes than men, the relative space occupied by the contents of the tunnel was not significantly different. This provides empirical evidence to counter the debate that the naturally smaller wrists of women may predispose them to the development of CTS as we found the relative space occupied within the carpal tunnel to be constant regardless of gender. The pinch grip posture used in this study resulted in a slightly non-oval distal carpal shape, reducing the effectiveness of carpal tunnel "flattening" ratios. Also, this was the first study to calculate and evaluate carpal tunnel volumes in non-neutral wrist postures. As part of that process, it became necessary to address the issue of off-axis (non-perpendicular) MRI slices that occur with deviated wrist postures. A simple correction for wrist angle resulted in significant reductions in distal cross-sectional area and carpal tunnel volume. In spite of numerous imaging studies that have reported cross-sectional areas of the carpal tunnel (Table 1), very few have altered scan planes with different wrist postures or considered the effects (Jessurun et al., 1987; Keberle et al., 2000).

Table 1
Cross-sectional area comparison table between the current study and the literature for proximal (P) and distal (D) levels of the tunnel in the extended (E), neutral (N) and flexed (F) postures

Study	Level	Cross-sectional area (mm^2)					
		Carpal tunnel			Tunnel contents		
		E	N	F	E	N	F
Current study	P	175	173	174	72	77	79
4F, 4M; 30° F/E	D	200	182	175	70	78	71
Corrected[a]	D	173	182	151	61		62
Jarvik et al. (2002)	P						
$N = 20$	D		203				
Monagle et al. (1999)	P		353			98	
15F, 10M	D		312				
Horch et al. (1997)	P	160	178	154			
12F, 5M; 45° F/E	D	180	152	144			
Cobb et al. (1997)	P						
$N = 7$	D		183			92	
Yoshioka et al. (1993)	P	151	173	145			
8F, 8M; 40°F, 50°E	D	187	158	138			
Cobb et al. (1992)	P		185			78	
$N = 5$	D		156			81	
Papaioannou et al. (1992)	P		275				
CT; 26M	D		263				
Skie et al. (1990)	P						
4F, 3M (bilat.); 45° F/E	D	175	152	136			
Jessurun et al. (1987)	P		195[b]				
CT; 5F, 5M (bilat.)	D		223[b]				
Merhar et al. (1986)	P		241			91[b]	
CT; 9F, 4M	D		206			81[b]	
Dekel et al. (1980)	P		242				
CT; 19F, 14M	D		228				

[a] Areas at distal carpal tunnel corrected by cos 30° deviated wrist postures.
[b] Calculated, or estimated, from data provided in study. A weighted average considering the number of male and female participants has been used.

Although this initial attempt was very simple, the choice to apply a correction process to slices that were not true cross-sections is important. Using the scout images, we found the mean wrist angle (between the longitudinal axes of the radius and second metacarpal) for all deviated postures to be $30° \pm 4°$. By applying a 'parallax correction factor' of cos 30° to the distal cross-sectional areas and an incremental correction for volumes in deviated postures, we attempted to account for the overestimation of the palmar-dorsal dimensions on out-of-plane scans (Table 1). Noting that the current data may differ from the literature, due to our use of a pinch grip posture and wrist angles of 30° rather than 40–50° as used in previous studies (Horch et al., 1997; Skie et al., 1990; Yoshioka et al., 1993), it is interesting to see that before correction, the distal carpal tunnel areas were similar to those in the literature (i.e. increasing with extension and decreasing with flexion) (Table 1). However, after applying the cos 30° correction factor, both flexed and extended wrists resulted in smaller carpal tunnel areas (Table 1). Both corrected and uncorrected CT volumes demonstrated a reduction from the neutral wrist, with the corrected volume for the extended wrist being the smallest, further supporting studies of carpal tunnel pressure (Keir et al., 1997; Werner et al., 1997) and the need for correction. Without this supporting evidence, this pressure increase has been proposed to be due to muscle incursion alone (Keir and Bach, 2000), which we were unable to measure in our data. While this method of adjustment resulted in significant changes in the current study, more information is required to determine whether similar correction factors would be beneficial if applied to previous data.

Irrespective of any corrections, this study has provided a more complete picture of the relationship between the carpal tunnel and its contents by examining ratios for area (CTC_A/CTA) and volume (CTC_V/CTV) in non-neutral postures. In Figs. 2 and 3, there is an obvious gender difference in the size of both tunnel and contents. However, there was no gender difference in the relative space occupied by the contents (Figs. 2 and 3, panel e vs f), or when dimensions were normalized to the neutral condition, supporting the findings of Monagle et al. (1999). While these data cannot counter the belt-pulley analogy that would predict higher force concentration (increased stress) in smaller wrists (Armstrong and Chaffin, 1978; Keir and Wells, 1999), it suggests that increases in CTP would be a function of wrist angle rather than wrist size.

Cross-sectional area of the CT (when normalized to neutral), its contents and the ratio between them (CTC_A/CTA) differed significantly depending on the level at which they were measured. While cross-sectional area remained relatively constant across postures at the proximal end of the carpal tunnel, it was significantly smaller at the distal end with wrist flexion. In neutral, we found the tunnel to be marginally larger at its distal end rather than tapered as found previously (Table 1) (Horch et al., 1997; Skie et al., 1990; Yoshioka et al., 1993). This was likely an effect of the pinch grip posture but has also been previously reported when scan planes were adjusted for posture (Jessurun et al., 1987). In the current study, both tunnel content area (CTC_A) and area ratio (CTC_A/CTA) were smallest at the distal end of the carpal tunnel in all conditions (except neutral, unloaded CTC_A which was constant). The area ratios in the current study ranged from 0.40 (extension-loaded) to 0.46 (neutral-loaded) (both at the pisiform). At the distal end of the carpal tunnel, we found the ratio of contents to space available (CTC_A/CTA) to be 19% lower in neutral than Cobb et al. (1992) (0.43 vs 0.54, respectively). Additionally, Cobb et al. (1992) reported smaller CTC_A and (CTC_A/CTA) proximally, using the radial styloid as the proximal boundary. In the current study, these measures were generally larger at the radial styloid than either the hook of the hamate or the pisiform.

After correction, wrist extension resulted in the smallest carpal tunnel volumes (Table 2). It should be noted that the current volumes are much smaller than Pierre-Jerome et al. (1997a,b) due to differences in boundary definitions and their use of conical sections to calculate volume. They measured from the distal radioulnar joint to the base of the metacarpal bones while using the carpal bones and the "trajectory of the flexor retinaculum" to define the dorsopalmar borders. Our observation correlates well with carpal tunnel pressure studies, which have consistently reported highest pressures with the wrist extended (Keir et al., 1998; Okutsu et al., 1989; Szabo and Chidgey, 1989). However, we also found the tunnel contents volume (Fig. 3c and d; Table 2) and CTC_V/CTV to be lowest in extension; the ratios being 0.37 in extension and 0.43 in both neutral and flexion (the neutral values being similar to Cobb et al., 1992) (Table 2). While the smaller carpal tunnel volume in extension supports CTP findings, the lower contents to tunnel ratio appears to be in conflict with this concept. Like previous studies (e.g. Cobb et al., 1992), our definition of carpal tunnel "contents" was limited to the flexor tendons and median nerve while excluding synovial sheaths and muscle tissue. The amount of muscle tissue within the tunnel has been shown to increase with incursion of the lumbricals during finger flexion (Cobb et al., 1994; Cobb et al., 1995; Yii and Elliot, 1994) and finger flexors in wrist extension (Holtzhausen et al., 1998; Keir and Bach, 2000). Despite planning to incorporate muscle tissue as part of the carpal tunnel contents, and while some muscle tissue was identifiable, equipment limitations (e.g. unavailability of the 3.0 T magnet) did not allow appropriate contrast of muscle tissue for digitization.

Loading of the flexor tendons using a pulp pinch had only a tendency to reduce the ratio between contents and carpal tunnel in area measures. Visually, the tendons were more tightly bundled within the tunnel, particularly when the wrist was deviated from neutral (the effect of loading on CTC_A approached but did not attain significance). Overall, while previous research suggested that the pinch grip might affect the tendons within the tunnel (Keir and Wells, 1999), we found that wrist posture and position in the carpal tunnel had greater effects on tunnel and content dimensions than the pinch grip used in this study. Other efforts to determine the nature of the anatomical changes in the carpal tunnel went relatively unrewarded. Median nerve and carpal tunnel flattening ratios were also calculated (the latter was not previously reported in the literature). However, due to the pinch grip, the tunnel did not remain as oval as thought, resulting in no significant differences in flattening ratios due to large variances. Our limited median nerve CSA and flattening ratios support the results of Monagle et al. (1999).

There were several limitations to the present study. First, due to technical issues, we were unable to use a 3 T MRI unit as planned, thus due to low tissue contrast

Table 2
Volume comparison table between the current study and the literature

Study	Volume (mm^3)						Ratio		
	Carpal tunnel			Tunnel contents			CTC_V/CTC		
	E	N	F	E	N	F	E	N	F
Current study									
Unloaded	3475	3737	3722	1261	1609	1571	0.37	0.43	0.43
Corrected	3312	3737	3553	1205	1609	1501			
Pinch (10 N)	3503	3742	3646	1229	1527	1482	0.36	0.40	0.40
Corrected	3339	3742	3481	1173	1527	1416			
Pierre-Jerome et al. (1997a)		10777							
Pierre-Jerome et al. (1997b)		10328							
Cobb et al. (1992)		4200			2000		0.48		
Corrected		3430							
Richman et al. (1987)		5840							
Corrected		4760							

In the current study, "corrected" values involved the application of an incremental angle change for the deviated wrist postures (as described in text). In previous studies, "correction" was a comparison to silicon moulds.

we were unable to include muscle tissue in measures of carpal tunnel contents as originally intended. Our data strongly suggest that measures of carpal tunnel contents are incomplete without including muscle tissue. Second, while a 3 mm slice thickness is smaller than often reported, the size of the slice thickness likely resulted in slight differences in the locations of the bony landmarks between trials. In addition, because the carpal bones were used as landmarks, some motion of the landmarks should be expected between postures. Third, the use of a 10 N thumb-index finger pinch may not have been sufficient to elicit an effect. While the force level was sufficient previously (Keir and Wells, 1999), the pinch posture itself may have resulted in different carpal tunnel shape changes than have been shown in prior studies. Finally, the correction factors used may not appropriately reflect the actual planes which intersect the carpal tunnel. A more in-depth examination of these correction factors has recently been performed via simulation.

In summary, this study represents a comprehensive approach to examining carpal tunnel dimensions in a variety of hand postures and loading conditions. There appears to be a need to correct for out-of-plane (non-cross-sectional) images as they had a significant effect on our data and may help explain findings in the literature. Wrist posture and the level of the carpal tunnel had greater impact on tunnel dimensions than tendon loading under the conditions tested. Carpal tunnel volume was smallest with the wrist extended, but the smallest carpal tunnel area was found in the distal carpal tunnel with a flexed wrist. Using the ratio between the carpal tunnel and its contents may provide an important method by which to assess the potential for compression of the median nerve, however, it is necessary to quantify muscle tissue within the carpal tunnel to achieve a more accurate representation of the contents. There is a need to incorporate participants at various stages of carpal tunnel syndrome in order to identify and compare tunnel dimensions and link carpal tunnel pressure in a diseased wrist.

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