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Wrist and carpal tunnel size and shape measurements: Effects of posture

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Abstract

Background. Wrist anthropometrics and posture have been implicated in the development of carpal tunnel syndrome, yet it remains unclear how external measurements relate to carpal tunnel parameters in neutral and non-neutral postures. The purposes of this study were (i) to evaluate the effect of slice orientation on several indices of carpal tunnel size and shape and (ii) to examine the relationship between carpal tunnel and external wrist dimensions.

Methods. Three-dimensional static models were generated to measure carpal tunnel and wrist parameters for six wrists in three wrist postures (30° flexion, neutral and 30° extension). A simulated imaging plane enabled measurement of four carpal tunnel dimensions and two shape indices throughout the tunnel length, using "axial" and "tunnel" slice orientations (perpendicular to forearm and tunnel, respectively).

Findings. Correction for tunnel orientation eliminated posture-related changes in tunnel size and shape noted at the distal end using "axial" alignment. "Tunnel" alignment reduced average carpal tunnel area and depth by nearly 15% in extension, but generally less than 5% in neutral and 2% in flexion. Subsequently, "tunnel" alignment also decreased carpal tunnel and non-circularity ratios to reveal a flatter, more elliptical shape throughout the tunnel in extension than neutral and flexion. Wrist dimensions correlated significantly with tunnel dimensions, but not tunnel shape, while wrist shape correlated significantly with tunnel shape, area and depth.

Interpretations. Slice alignment with the carpal tunnel may improve the consistency of findings within and between patient and control populations, and enhance the diagnostic utility of imaging in clinical settings.

Keywords: Carpal tunnel syndrome; MRI; Volume; Wrist; Three-dimensional reconstruction; Modelling; Wrist anthropometrics; Carpal tunnel dimensions; Shape analysis

1. Introduction

Carpal tunnel syndrome (CTS) is the most common peripheral entrapment neuropathy (Rempel and Diao, 2004), wherein increased carpal tunnel pressure and mechanical compression compromise median nerve function. Deviated wrist postures represent a workplace risk factor, particularly with forceful and/or repetitive hand use (Tanzer, 1959; Smith et al., 1977; Armstrong and Chaffin, 1979; Silverstein et al., 1987). Anatomical, physiological and behavioural differences likely help explain why only certain workers develop symptoms (Szabo, 1998). Anthropometric comparison of patient and control groups indicates that wrist and hand dimensions may contribute to CTS development, leading some epidemiologists and clinicians to use anthropometrics to identify individuals at greater risk (Gordon et al., 1988; Radecki, 1994; Chroni et al., 2001; Boz et al., 2004; Kamolz et al., 2004; Moghtaderi et al., 2005). Stronger association between CTS and wrist ratio (depth/width quotient) than wrist circumference suggests wrist shape is more relevant than size (Moghtaderi et al., 2005). While correlations may inferentially link anthropometrics and median nerve function, no significant relationship between wrist and carpal tunnel dimensions has been identified (Bleecker et al., 1985; Uchiyama

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et al., 2005). However, previous studies examined only a single measure in relation to wrist circumference, warranting a more detailed assessment of internal and external parameters.

Carpal tunnel size and shape have been implicated in median nerve compression, with smaller carpal tunnel cross-sectional area (CTA) and narrowed dimensions representing mechanisms for increased hydrostatic pressure and mechanical impingement (Keir and Rempel, 2005). Comparisons of CTA between patients and healthy controls exist for a neutral wrist posture at the pisiform and hook of the hamate, but the results are equivocal. Numerous studies have reported smaller CTA in patient groups than controls, supporting the hypothesized link between smaller tunnel size and CTS (Dekel et al., 1980; Gelmers, 1981; Bleecker et al., 1985; Papaioannou et al., 1992; Horch et al., 1997). However, other studies have reported larger areas in patients than controls (Winn and Habes, 1990; Uchiyama et al., 2005), while others found no significant difference (Merhar et al., 1986; Jessurun et al., 1987; Cobb et al., 1997; Monagle et al., 1999). These discrepancies emphasize that CTA is likely not a distinct anatomic risk factor, and may explain its reported non-significant correlation with wrist circumference (Bleecker et al., 1985). Quantitative analysis of carpal tunnel shape is less common, typically evaluated using ratios between tunnel width and depth (Kamolz et al., 2004; Bower et al., 2006). While such ratios may reasonably approximate elliptical dimensions, they may be misleading for more irregularly shaped cross-sections (Bower et al., 2006). The relationship between cross-sectional area and circumference has been used to demonstrate varying degrees of circularity between nerve fibre types (Arbuthnott et al., 1980). Similar evaluation of the carpal tunnel may help determine potential sites of median nerve compression.

Carpal tunnel area is known to change with wrist posture. In the neutral wrist posture, CTA is typically reported to be larger proximally than distally (Dekel et al., 1980; Merhar et al., 1986; Yoshioka et al., 1993; Horch et al., 1997; Pierre-Jerome et al., 1997; Monagle et al., 1999). This relationship holds in flexion, with proximal and distal decreases in CTA, but reverses in extension due to a proximal decrease and distal increase in area (Skie et al., 1990; Yoshioka et al., 1993; Horch et al., 1997; Bower et al., 2006). However, these results appear consistent with non-perpendicular alignment of the imaging plane relative to the carpal tunnel (Mogk and Keir, 2007), and are contrary to the invariant CTA reported when slice orientation was matched to each wrist angle (Jessurun et al., 1987). Further complicating CTA interpretation, computerized reconstructions reveal disparities between carpal tunnel orientation and external wrist angle, with a slightly extended tunnel orientation even in 30° wrist flexion (Mogk and Keir, 2007). While previous reconstruction demonstrated the effects of image orientation on apparent tunnel size and shape, quantitative analysis was limited to CTA (Mogk and Keir, 2007). The purposes of this study were (i) to evaluate the effect of slice orientation on carpal tunnel dimensions using several indices of size and shape and (ii) to examine the relationship between carpal tunnel and external wrist dimensions.

2. Methods

Three-dimensional models were created previously by combining reconstructed MRI data and modelled bone surfaces, described in detail by Mogk (2007). Digitized contours of the skin (wrist/hand), bones and carpal tunnel of six individuals (4 males, 2 females) were imported into the Maya™ platform (v7.0, Alias®, Toronto, Canada) to reconstruct the skin and carpal tunnel surfaces, and bone positions in three splinted wrist postures (30° flexion, neutral and 30° extension). Wrists were imaged with the hand in a pulp pinch posture. Individuals had a mean age of 26.8 (SD 2.1) years, wrist circumference of 16.3 (1.4) cm and wrist width of 6.5 (0.6) cm.

Three static models were constructed for each individual (one per posture), recreating the posture-specific bone positions using anatomical bone surfaces (radius, ulna, 8 carpals and 5 metacarpals) placed according to the digitized bone contours. The radius and ulna were fixed, and served to align all structures (skin, bones and carpal tunnel) in each posture. Reconstructed skin and carpal tunnel surfaces were used to determine wrist and carpal tunnel dimensions, with visual reference to the bony anatomy.

2.1. Wrist dimension measurements

Wrist dimensions were measured using reconstructed skin surfaces in all three wrist postures. A measurement plane, or "cut-line", was created perpendicular to the long axis of the forearm (as defined at the time of imaging) to transect the skin surface and enable measurement of wrist circumference, width (medial–lateral distance), depth (palmar–dorsal distance) and cross-sectional area. Medial–lateral and palmar–dorsal distances were acquired using a caliper-like measurement, ensuring perpendicular alignment of the two diameters. Wrist ratio was calculated as wrist depth divided by wrist width (Gordon et al., 1988). The cut-line was positioned at the distal end of the radial styloid to approximate the distal wrist crease, and maintained for all three wrist postures since little displacement is expected with motion (Bugbee and Botte, 1993).

2.2. Carpal tunnel measurements

The bone surfaces were used to identify the carpal tunnel boundaries, with the proximal border running between specific vertices identified on the pisiform and scaphoid tubercle, and the distal border lying between the distal hook of the hamate and trapezial ridge (Mogk, 2007). This ensured that measurements in each posture lay within the anatomically "landmarked" volume. Carpal tunnel cross-sectional area (CTA), circumference (CIRC), width

(CTW) and depth (CTD) were measured at 1.5 mm increments using the measurement plane aligned perpendicular to the long axis of the tunnel. Although CTW and CTD are typically equated with medial–lateral and palmar–dorsal distances, respectively, the tunnel was often rotated about the long axis of the forearm. Consequently, tunnel width and depth measurements often required slice-by-slice rotation of the caliper-like tool relative to the wrist (Fig. 1). The widest distance represented CTW, with CTD measured perpendicular to the width.

Two ratios were also calculated to evaluate carpal tunnel shape. The first, carpal tunnel ratio (CTR), was calculated as the ratio of tunnel depth to tunnel width (Kamolz et al., 2004), and is equivalent to the inverse of the "flattening" ratio adopted from median nerve studies (c.f. Bower et al., 2006). CTR is analogous to wrist ratio, with values smaller than 1.0 when tunnel width exceeds its depth. The second shape index, non-circularity ratio (NCR) (Arbuthnott et al., 1980), was calculated as the ratio between CTA and the area of a circle with the same circumference, or

$$\text{Non-circularity} = \frac{4\pi * \text{CTA}}{\text{circumference}^2} \quad (1)$$

The NCR results in a maximum value of 1.0 (perfect circle), with smaller values indicating less circular or elongated shapes. Measurements were evaluated at the proximal (scaphoid tubercle) and distal ends (distal extent of ridge of trapezium). An "average" measurement was also calculated using all slices throughout the carpal tunnel length.

The effect of non-perpendicular imaging on carpal tunnel dimensions and shape indices was evaluated by rotating the measurement plane about the flexion-extension axis (Fig. 2). Measurements acquired using the typical axial slice orientation (perpendicular to forearm) were compared to those determined with the cut-line aligned perpendicular to the carpal tunnel. Slice-by-slice adjustments were made to account for tunnel curvature in each posture, rotating each slice about its midpoint to obtain a "physiological" cross-section (perpendicular to the tunnel). For brevity, subscript terms indicate measurement slice orientation; subscript "A" signifies the typical "axial" alignment relative to the forearm, while "T" denotes slice-by-slice alignment relative to the carpal tunnel.

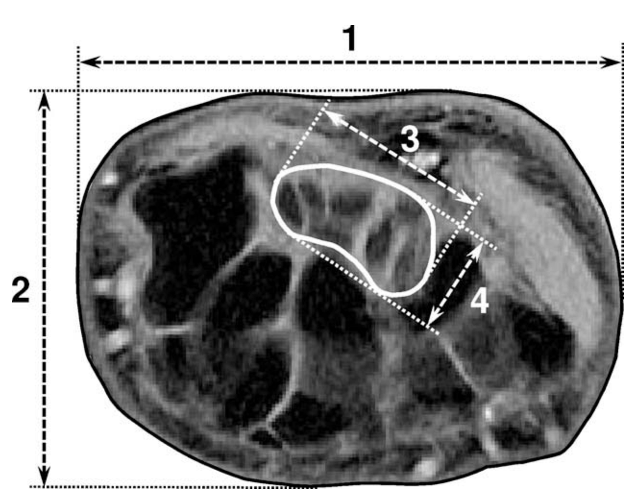

Fig. 1. Schematic showing defined wrist and carpal tunnel dimensions: (1) wrist width, (2) wrist depth, (3) carpal tunnel width (CTW) and (4) carpal tunnel depth (CTD). Note that, at this location, the carpal tunnel is rotated nearly 30° relative to the medial–lateral and dorso–palmar directions of the wrist.

2.3. Statistics

Repeated measures ANOVAs and planned comparisons were performed to evaluate the effects of slice orientation (axial, tunnel), wrist posture (30° extension, neutral, 30° flexion) and tunnel location (proximal, distal, average) on each carpal tunnel dimension (STATISTICA, v6.0, StatSoft Inc., Tulsa, OK, USA). Significance was set at $P = 0.05$ with a Bonferroni correction factor applied where necessary for contrast analyses. Unless an F-statistic is presented, P-values reflect those determined using planned contrasts. Correlational matrices were used to determine the strength of relationships between internal and external dimensions.

3. Results

3.1. Carpal tunnel

3.1.1. Carpal tunnel cross-sectional area

A significant three-way interaction was found between slice orientation, wrist posture and tunnel location ($F_{4,20} = 3.7$, $P < 0.05$), and a main effect of slice orientation ($F_{1,5} = 44.6$, $P = 0.001$). Proximally, CTA_T measures were 8.7% (SD 5.5%) smaller than CTA_A in extension ($P < 0.05$), 2.2% (2.3%) in neutral and 2.6% (3.3%) in flexion (Table 1). Distally, CTA_T was 14.6% (5.3%) smaller than CTA_A in extension ($P < 0.01$), 3.3% (2.8%) in neutral ($P < 0.05$), and 1.2% (1.7%) in flexion (Table 1). Average CTA_T was smaller than average CTA_A in extension ($P < 0.001$) and neutral ($P = 0.01$), with a similar trend in flexion. Distal CTA_A was larger in extension than both neutral and flexion ($P < 0.01$), while average CTA_A was larger in extension than flexion ($P = 0.01$). In contrast, proximal CTA_T was smaller in extension than neutral ($P < 0.01$) and flexion ($P < 0.05$), while average CTA_T was significantly smaller in extension than neutral ($P < 0.05$) and flexion ($P = 0.01$).

3.1.2. Carpal tunnel circumference

Tunnel circumference varied significantly with the three-way interaction between slice orientation, wrist posture and tunnel location ($F_{4,20} = 10.6$, $P < 0.001$). Main effects were found for slice orientation ($F_{1,5} = 42.1$, $P = 0.001$), wrist posture ($F_{2,10} = 6.0$, $P < 0.05$) and tunnel location ($F_{2,10} = 19.4$, $P < 0.001$). Distally, $CIRC_T$ was 4.6% (1.7%) smaller than $CIRC_A$ in extension ($P < 0.001$), while

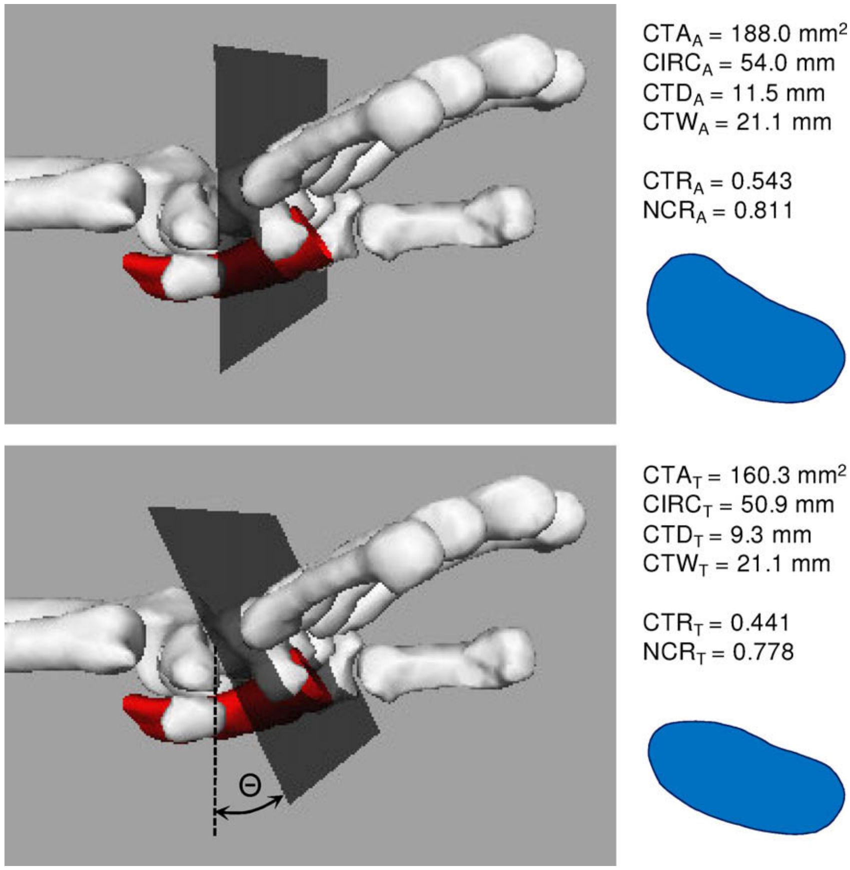

Fig. 2. Illustration of the static model for one wrist, in the extended posture, showing differences in carpal tunnel dimensions and shape index values obtained using "axial" (top) and "tunnel" (bottom) alignment of the measurement plane, for one slice at the distal end of the tunnel.

average $CIRC_T$ was 2.9% (2.1%) smaller than average $CIRC_A$ ($P < 0.001$) (Table 1). $CIRC_A$ was larger proximally than distally in neutral ($P < 0.01$), and smaller at the proximal end in flexion than neutral ($P = 0.01$) and extension ($P < 0.05$). Distal $CIRC_A$ was also larger in extension than flexion ($P = 0.01$), with smaller average $CIRC_A$ in flexion than extension ($P = 0.01$) and neutral ($P < 0.01$). Within the $CIRC_T$ measures, the proximal end was larger than the distal in extension ($P < 0.05$) and neutral ($P < 0.01$), while proximal and average $CIRC_T$ were smaller in flexion than neutral ($P < 0.05$ and $P = 0.01$, respectively).

3.1.3. Carpal tunnel depth

A significant three-way interaction was found between slice orientation, wrist posture and tunnel location ($F_{4,20} = 6.3$, $P < 0.01$). Slice orientation also had a main effect on tunnel depth ($F_{1,5} = 53.4$, $P < 0.001$). CTD_T was 1.8 (0.6) mm shallower than CTD_A at the distal end in extension, equating to a mean reduction of 15.9% (5.2%) ($P < 0.001$; Table 1). Average CTD_T was smaller than average CTD_A in all three wrist postures, with an 11.9% (7.1%) difference in extension ($P < 0.001$), 2.5% (2.8%) in neutral ($P = 0.01$) and 1.1% (1.8%) in flexion ($P = 0.01$). Distal CTD_A was shallower than proximal in flexion ($P < 0.01$), but deeper than proximal in extension ($P < 0.05$) and greater in extension than neutral ($P = 0.01$). Using CTD_T, the proximal tunnel was shallower in extension than neutral ($P < 0.01$) or flexion ($P < 0.01$). Average CTD_T was shallower (throughout tunnel length) in extension than in neutral ($P = 0.001$) and flexion ($P < 0.01$). Distal CTD_T did not differ significantly between wrist postures, and no differences were noted between proximal and distal ends in any posture.

3.1.4. Carpal tunnel width

Tunnel width had a two-way interaction between wrist posture and tunnel location ($F_{4,20} = 3.8$, $P < 0.05$). No significant differences were found between axial and tunnel slice orientations. The proximal end was wider than the distal in extension ($P = 0.01$) and neutral ($P < 0.01$), and narrowed from neutral to flexion ($P = 0.01$) (Table 1). No significant differences were noted at the distal end between postures.

3.1.5. Carpal tunnel shape

The ratio of CTD to CTW varied significantly with the three-way interaction of slice orientation, wrist posture and tunnel location ($F_{4,20} = 4.9$, $P < 0.01$). Main effects were observed for slice orientation ($F_{1,5} = 45.5$, $P = 0.001$) and

Table 1
Comparison of mean (SD) carpal tunnel dimensions using "axial" and "tunnel" measurement plane alignments, in each of the three wrist postures examined

Tunnel dimension	Slice orientation	Tunnel location	Wrist posture					
			30° Extension		Neutral		30° Flexion	
Cross-sectional area (CTA)	"Axial"	Proximal	179.4 (25.3)	d	184.4 (18.5)		177.3 (22.9)	
		Distal	188.4 (29.7)	B, e	176.6 (22.0)	e	174.3 (26.0)	B
		Average	183.0 (26.4)	B, f	179.6 (20.8)	f	176.7 (22.4)	B
	"Tunnel"	Proximal	163.6 (23.3)	A, B, d	180.5 (19.7)	A	172.4 (20.7)	B
		Distal	160.9 (26.6)	e	170.8 (21.6)	e	172.2 (25.6)	
		Average	162.4 (26.2)	A, B, f	175.0 (20.3)	A, f	173.4 (21.1)	B
Circumference (CIRC)	"Axial"	Proximal	55.4 (3.5)	B	55.0 (3.2)	C, a	52.6 (2.8)	B, C
		Distal	54.4 (4.5)	B, e	52.9 (3.2)	a	51.9 (3.6)	B
		Average	54.4 (3.9)	B, f	53.1 (3.2)	C	52.0 (2.9)	B, C
	"Tunnel"	Proximal	54.6 (3.5)	a	54.9 (3.4)	C, a	52.3 (2.9)	C
		Distal	51.9 (4.8)	a, e	52.3 (3.4)	a	51.8 (3.6)	
		Average	52.7 (4.0)	f	52.7 (3.3)	C	51.8 (2.9)	C
Carpal tunnel depth (CTD)	"Axial"	Proximal	10.1 (1.2)	a	10.7 (0.7)		11.0 (1.4)	a
		Distal	11.4 (0.5)	A, a	10.6 (0.7)	A	10.6 (1.4)	a
		Average	10.7 (1.0)	f	10.7 (0.8)	f	10.9 (1.3)	f
	"Tunnel"	Proximal	9.3 (1.0)	A, B	10.5 (0.6)	A	10.8 (1.0)	B
		Distal	9.5 (0.7)		10.1 (0.7)		10.5 (1.5)	
		Average	9.3 (1.0)	A, B, f	10.4 (0.7)	A, f	10.7 (1.3)	B, f
Carpal tunnel width (CTW)	"Axial"	Proximal	23.0 (1.4)	a	22.5 (1.6)	C, b	20.9 (1.5)	C
		Distal	21.6 (2.1)	a	21.5 (1.5)	b	21.0 (1.5)	
		Average	22.0 (1.6)		21.4 (1.5)		20.7 (1.2)	
	"Tunnel"	Proximal	23.1 (1.4)		22.5 (1.6)		20.9 (1.4)	
		Distal	21.4 (2.1)		21.4 (1.6)		21.0 (1.5)	
		Average	22.0 (1.6)		21.4 (1.5)		20.7 (1.2)	

Units for cross-sectional area are mm^2, while circumference, width and depth are all in mm. For each carpal tunnel measure, significant differences between postures are indicated using capital letters, while differences between tunnel location and slice orientation are indicated with lower case letters.
Postural (columnar) comparisons: A = extension vs. neutral; B = extension vs. flexion; and C = neutral vs. flexion.
Tunnel level and slice orientation (row) comparisons: a = proximal vs. distal; b = proximal vs. average; c = distal vs. average; d = proximal axial vs. tunnel; e = distal axial vs. tunnel; and f = average axial vs. tunnel.

posture ($F_{2,10} = 4.7$, $P < 0.05$). Distal CTR_T was smaller (i.e. more elliptical or flatter in appearance) than CTR_A in extension ($P < 0.01$), with a similar trend in neutral ($P < 0.05$) (Table 2). Average CTR_T (throughout tunnel

Table 2
Comparison of mean (SD) shape index ratios acquired using "axial" and "tunnel" measurement plane alignments, in each of the wrist postures examined

Shape index	Slice orientation	Tunnel location	Wrist posture					
			30° Extension		Neutral		30° Flexion	
Carpal tunnel ratio (CTR)	"Axial"	Proximal	0.437 (0.040)		0.479 (0.039)		0.530 (0.089)	
		Distal	0.530 (0.056)	e	0.491 (0.031)		0.506 (0.053)	
		Average	0.487 (0.037)	f	0.501 (0.040)	f	0.526 (0.072)	f
	"Tunnel"	Proximal	0.401 (0.035)	A, B	0.467 (0.029)	A	0.516 (0.063)	B, a
		Distal	0.447 (0.036)	e	0.474 (0.032)		0.498 (0.057)	a
		Average	0.425 (0.034)	A, B, f	0.487 (0.035)	A, f	0.519 (0.068)	B, f
Non-circularity ratio (NCR)	"Axial"	Proximal	0.730 (0.038)	a, d	0.765 (0.037)		0.803 (0.068)	
		Distal	0.797 (0.026)	a, e	0.789 (0.024)		0.808 (0.034)	
		Average	0.775 (0.029)		0.799 (0.031)		0.820 (0.050)	
	"Tunnel"	Proximal	0.686 (0.037)	B, d	0.752 (0.026)	a	0.792 (0.058)	B
		Distal	0.746 (0.022)	A, B, e	0.781 (0.025)	A, a	0.804 (0.035)	B
		Average	0.729 (0.035)		0.789 (0.027)		0.815 (0.049)	

Note, smaller carpal tunnel ratio values indicate tunnel "flattening", while smaller non-circularity ratio values signify a less round appearance. For each shape index, significant differences between postures are indicated using capital letters, while differences between tunnel location and slice orientation are indicated with lower case letters.
Postural (columnar) comparisons: A = extension vs. neutral; B = extension vs. flexion; and C = neutral vs. flexion.
Tunnel level and slice orientation (row) comparisons: a = proximal vs. distal; b = proximal vs. average; c = distal vs. average; d = proximal axial vs. tunnel; e = distal axial vs. tunnel; and f = average axial vs. tunnel.

length) was smaller than CTR_A in all three wrist postures (all $P < 0.01$). CTR_A showed no significant differences between postures or tunnel locations. Using CTR_T, the proximal end appeared flatter in extension than neutral ($P < 0.05$) and flexion ($P < 0.01$). The distal end was flatter than the proximal in flexion ($P < 0.01$), but no differences were noted distally between wrist postures. The carpal tunnel was flatter in appearance throughout its length in extension than neutral ($P < 0.001$) and flexion ($P < 0.01$).

Significant two-way interactions were found for NCR between slice orientation and wrist posture ($F_{2,10} = 35.7$, $P < 0.001$) as well as posture and tunnel location ($F_{4,20} = 4.7$, $P < 0.01$). Main effects were observed for slice orientation ($F_{1,5} = 58.9$, $P < 0.001$), wrist posture ($F_{2,10} = 9.7$, $P < 0.001$) and tunnel location ($F_{1,5} = 22.7$, $P < 0.001$). NCR_A was generally rounder in appearance (larger ratio) than NCR_T (Table 2), with significant differences in extension at both the proximal ($P = 0.01$) and distal ends ($P < 0.01$). NCR_A was larger distally than proximally in extension ($P < 0.01$), while NCR_T was rounder distally than proximally in all postures, but significantly only in neutral ($P < 0.001$). In extension, NCR_T was less round proximally than flexion ($P = 0.01$), and distally relative to neutral ($P < 0.05$) and flexion ($P = 0.01$).

3.1.6. Relationships between carpal tunnel dimensions

Regression analyses, incorporating all slices for each wrist in all three postures, revealed that CTA_T was most highly correlated with $CIRC_T$ ($r = 0.815$) and CTD_T ($r = 0.778$), and least correlated with CTW_T ($r = 0.479$). Controlling for circumference and width, the partial correlation coefficient between CTA_T and CTD_T increased to 0.810.

3.2. Wrist dimensions

Wrist dimensions measured from the neutral wrist posture at the time of imaging (circumference and depth) were not significantly different from measurements obtained from the reconstructed skin surfaces. Using the reconstructed skin surfaces, a significant main effect of wrist posture was found for wrist circumference ($F_{2,10} = 5.5$, $P < 0.05$), depth ($F_{2,10} = 16.5$, $P < 0.001$) and cross-sectional area (CSA; $F_{2,10} = 7.7$, $P = 0.01$). Wrist circumference was larger in flexion than neutral ($P < 0.05$), while both wrist depth and CSA were larger in flexion than extension ($P < 0.01$ and $P < 0.05$, respectively) and neutral ($P < 0.01$ and $P < 0.05$, respectively). Neither wrist width nor wrist ratio varied significantly with wrist posture.

3.2.1. Relationships between wrist and carpal tunnel measures

Correlations performed separately for each posture revealed similar coefficients between postures, thus correlations were repeated including all three wrist postures ($n = 18$; six individuals and three postures). The highest correlations were found between CTA_T and wrist circumference ($r = 0.835$–0.870), wrist CSA ($r = 0.860$–0.894) and wrist depth ($r = 0.883$–0.941) (Table 3). Wrist dimensions were not significantly correlated with either tunnel shape index (CTR_T and NCR_T). Wrist ratio was most highly correlated with CTD ($r = 0.617$–0.736), but was not significantly correlated with tunnel width or circumference (Table 3).

4. Discussion

Building upon previous findings (Mogk and Keir, 2007), static three-dimensional models were constructed to examine posture-related changes in carpal tunnel size and shape. With the uncertainty of slice orientation used in previous studies, the current investigation compared results obtained using the traditional "axial" alignment (perpendicular to forearm) with measurements using slices perpendicular to the carpal tunnel. Measures made perpendicular to the tunnel reduced the apparent carpal tunnel area, circumference and depth compared to "axial" alignment, while width was unchanged. The most notable effect of slice orientation occurred in the extended posture, particularly at the distal end where significant posture-related changes in tunnel size and shape disappeared with correction for tunnel orientation, which is consistent with Jessurun et al. (1987). The NCR, used previously to differentiate nerve fibre types (Arbuthnott et al., 1980), was introduced to address difficulties in assessing irregularly shaped cross-sections using width-depth ratios.

The current investigation of posture-related changes in carpal tunnel size and shape compared measures obtained using "axial" and "tunnel" alignment to assess the effect of slice orientation on tunnel dimensions. Note that this was accomplished using computerized analogs of each carpal tunnel and a simulated imaging plane rather than re-imaging wrists under each alignment definition. This comprehensive comparison was necessary to evaluate the results of previous studies which have focused on CTA, since few studies have indicated altered scan orientation to account for changes in wrist or tunnel angle (Jessurun et al., 1987; Keberle et al., 2000). Relative to neutral, "axial" cross-sections revealed reductions in CTA_A and CTD_A both proximally and distally in flexion, while extension caused the CTA_A and CTD_A to decrease proximally but increase distally (Table 1). Conversely, "tunnel" cross-sections showed CTA_T and CTD_T to decrease throughout the tunnel length in the extended posture. Moreover, CTR_A and NCR_A indicated a flatter and more elliptical appearance proximally than distally in both extension and neutral, while the reverse occurred in flexion (Table 2). In contrast, "tunnel" alignment revealed a flatter, more elliptical shape throughout in extension compared to neutral and flexion. Results obtained using "axial" alignment corroborate previous findings of posture-related changes in CTA, and the generally subjective reports of tunnel shape in each posture (Skie et al., 1990; Yoshioka et al., 1993; Horch et al., 1997; Bower et al.,

Table 3
Correlations (*r*-value) between wrist and carpal tunnel measures (dimensions and shape indices)

Carpal tunnel measure	Tunnel location	Wrist measure				
		Cross-sectional area	Circumference	Width	Depth	Wrist ratio
Cross-sectional area	Proximal	0.860***	0.835***	0.770***	0.883***	0.625**
	Distal	0.894***	0.870***	0.814***	0.923***	0.617**
	Average	0.881***	0.852***	0.790***	0.941***	0.707***
Circumference	Proximal	0.716***	0.712***	0.694***	0.688**	0.291
	Distal	0.880***	0.865***	0.838***	0.875***	0.480*
	Average	0.876***	0.864***	0.850***	0.864***	0.411
Width	Proximal	0.446	0.453	0.475*	0.402	0.012
	Distal	0.818***	0.809***	0.801***	0.794***	0.362
	Average	0.673**	0.671**	0.702***	0.626**	0.123
Depth	Proximal	0.695***	0.658**	0.554*	0.748***	0.736***
	Distal	0.714***	0.686**	0.597**	0.767***	0.617**
	Average	0.693***	0.662**	0.565*	0.768***	0.736***
Carpal tunnel ratio	Proximal	0.320	0.285	0.188	0.384	0.588**
	Distal	0.282	0.243	0.154	0.356	0.582**
	Average	0.265	0.239	0.135	0.354	0.589**
Non-circularity ratio	Proximal	0.313	0.278	0.199	0.388	0.577**
	Distal	0.127	0.101	0.016	0.224	0.457
	Average	0.191	0.155	0.055	0.328	0.682**

Asterisks are used to indicate the level of significance.
* Significance at $P \leqslant 0.05$.
** Significance at $P \leqslant 0.01$.
*** Significance at $P \leqslant 0.001$.

2006). This supports the re-examination of tunnel dimensions in neutral and non-neutral wrist postures, as current results suggest that our existing perception of posture-related changes in carpal tunnel dimensions is based primarily on studies that did not alter slice orientation with wrist angle.

Correction of measurement plane orientation to acquire more "physiological" cross-sections in each posture altered the apparent size and shape of the carpal tunnel (Fig. 2), and the relative changes between postures. "Tunnel" slice alignment reduced measured dimensions, particularly at the distal end in the extended posture. CTW was the only measure not altered by slice orientation, although reductions in circumference from "axial" alignment (less than 5%) might be regarded as negligible. Stating non-perpendicular distortion relative to "tunnel" orientation, "axial" alignment (CTA_A) overestimated mean CTA_T by 13.0% (SD 8.2%) in extension (9.8% proximally and 17.4% distally), while mean depth (CTD_A) was 14.3% (9.3%) larger than CTD_T (8.4% proximally and 19.3% distally). Subsequently, both shape indices decreased with "tunnel" slice alignment, revealing a flatter, more elliptical tunnel shape throughout in extension compared to neutral and flexion (Table 2). "Axial" overestimation of CTA_T and CTD_T was generally less than 5% in neutral and 2% in flexion. Relative overestimation using CTA_A is slightly larger than previously reported (Mogk and Keir, 2007), likely resulting from the current use of slice-by-slice adjustments rather than assuming a single representative tunnel orientation in each posture. Despite the comparable relative decreases from "axial" to "tunnel" alignment, CTD_T explained only 65% of the variance in CTA_T. Average CTA_T (throughout the tunnel) was largest in neutral and smallest in extension, supporting greater pressure increases with extension compared to flexion (Gelberman et al., 1981; Rojviroj et al., 1990; Weiss et al., 1995; Keir et al., 1997; Werner et al., 1997; Luchetti et al., 1998). Relative to the neutral posture, proximal CTA_T decreased more with extension than flexion, while distal CTA_T decreased with extension and increased with flexion (Table 1), supporting distal pressure increases in extension and proximal increases with flexion and extension (Tanzer, 1959; Luchetti et al., 1998). The distal increase in CTA_T (in flexion) appears to be due to an increase in CTD_T, indicating greater retinacular bowing, since changes in CTW_T were minimal (Table 1). The relatively constant distal end width between wrist postures supports previous findings (Garcia-Elias et al., 1992; Yoshioka et al., 1993; Fuss and Wagner, 1996). Correction for tunnel orientation provided a truer representation of the posture-related changes in tunnel size and shape, and helped clarify discrepancies between imaging and pressure studies. These findings demonstrate the importance of imaging plane alignment and support the use of sagittal scout images to improve slice orientation relative to the tunnel angle. Similar adjustments can be made for radioulnar deviation and forearm rotation, enabling investigation of combined wrist and forearm postures on tunnel dimensions.

The decision to investigate the NCR resulted from concern raised over the effectiveness of using width-depth ratios to evaluate the "shape" of non-elliptical cross-sections (Bower et al., 2006). CTR is analogous to wrist ratio, stating tunnel depth as a proportion of tunnel width. Interestingly, while wrist ratio is commonly used to indicate wrist "squareness" (c.f. Gordon et al., 1988), CTR is typically interpreted to reflect how elliptical or flattened the tunnel appears. Nevertheless, its utility as a shape index might be questioned based on its inability to differentiate between cross-sections with the same width and depth; regardless of shape, they possess equivalent CTR values (Fig. 3). However, the NCR (relating CTA and CIRC) reveals an ellipse to be rounder in appearance than an irregularly shaped cross-section (Fig. 3). Furthermore, previous studies have equated tunnel depth and width with palmar–dorsal and medial–lateral distances, respectively (Yoshioka et al., 1993; Kamolz et al., 2004), or the major and minor axis lengths of an equivalent ellipse (Bower et al., 2006). For a given cross-section, each of these definitions could result in a unique CTR value, whereas the NCR does not possess the same directionality. Although further investigation is required to evaluate its sensitivity to differences in shape, the NCR accounts for shape irregularities resulting from bony projections and may prove valuable in locating sites of impingement. Furthermore, with CTS patients showing a rounder tunnel appearance due to increased palmar bowing of the retinaculum (Horch et al., 1997; Monagle et al., 1999; Uchiyama et al., 2005), the NCR may provide a simpler method to assess retinacular bowing.

Correlation analyses performed between internal and external parameters indicate a relationship between posture-related changes in wrist and carpal tunnel dimensions and shape. Wrist dimensions correlated significantly with carpal tunnel dimensions only, but not tunnel shape, while wrist ratio (shape) correlated significantly with tunnel shape, area and depth (Table 3). Although several studies have indicated an association between wrist shape and median nerve function, few have examined potential relationships between wrist and carpal tunnel parameters. The significant relationship found between wrist circumference and CTA (Table 3) is contrary to previous findings (Bleecker et al., 1985); however, use of the variably located

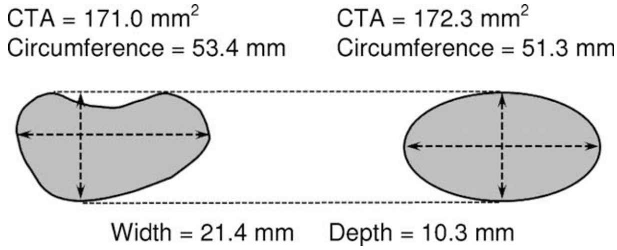

Fig. 3. Comparison of the digitized cross-section from Fig. 1 (left) with the equivalent ellipse (right) constructed from the measured width and depth parameters. Despite obvious differences in shape, the carpal tunnel ratio equates both with a value of 0.480 (i.e. width is almost twice the depth). Conversely, NCR (see Eq. (1)) results in values of 0.753 (left) and 0.824 (right), indicating a rounder appearance of the equivalent ellipse.

"smallest" area in that study might have precluded significance. Uchiyama et al. (2005) found no correlation between wrist circumference and retinacular bowing, the latter being correlated with CTA, but only in CTS patients. A relationship was recently reported between wrist and CTRs, but was based on differences noted between patient and control groups rather than correlation (Kamolz et al., 2004). The current study supports this association between wrist and carpal tunnel shape indices (Table 3). While the current analyses are considered preliminary, based on the small number of individuals, they provide insight into the reported association between wrist dimensions and the potential risk of developing CTS.

This study represents a comprehensive evaluation of carpal tunnel size and shape in neutral and non-neutral wrist postures, using an MRI-based modelling approach, and enabled examination of the relationship between wrist and carpal tunnel dimensions based on bone geometry. Current results suggest that our previous understanding of posture-related changes in tunnel dimensions reflects slices aligned relative to the forearm, rather than the carpal tunnel itself. Although correction for tunnel orientation had a smaller effect at the proximal end, the current results indicate that adjustment may be desirable distally even in neutral where "axial" alignment increased tunnel dimensions by more than 5% in some wrists. Slice alignment with the tunnel may improve the consistency of findings within and between patient and control populations, and enhance the diagnostic utility of imaging studies. Similar consideration is required when investigating the median nerve and finger flexor tendons to determine the amount of relative space within the carpal tunnel or evaluate potential nerve flattening. While posture-related changes in CTA were most highly correlated with wrist depth, further investigation is required to determine the potential relationship between wrist and carpal tunnel dimensions and median nerve function.

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