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COMMUNICATION

CLINICAL ANATOMY WILEY

External wrist ratio is not a proxy for internal carpal tunnel shape: Implications for evaluating carpal tunnel syndrome risk

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Abstract

Carpal tunnel syndrome (CTS) is highly prevalent, resulting in decreased function and increased need for costly healthcare services. External wrist ratio (depth/width >0.70) is a strong predictor of the development of CTS and has been suggested to be a proxy for internal carpal tunnel (CT) shape. Conversely, sonography can more directly evaluate CT shape. The purpose of our study was to explore the relationship between wrist ratio and sonographic CT measurements to (1) evaluate the reliability of sonographic CT measurements and (2) explore how external wrist measures relate to anthropometric features of the CT. We used sonographic imaging on a sample of healthy participants ($n = 226$) to measure CT cross-sectional area, depth, width, and depth/width ratio. We conducted exploratory correlation and regression analyses to identify relationships of these measures with external wrist ratio. Reliability for dominant and nondominant sonographic CT measures ranged from good to excellent (0.79–0.95). Despite a moderate correlation between CT width and depth and their external wrist counterparts (0.33–0.41, $p < 0.001$), wrist ratio and CT ratio demonstrated weak to no correlation (dominant: $r = 0.12$, $p = 0.053$; nondominant: $r = 0.20$, $p = 0.002$) and the mean CT ratio was far lower than the mean wrist ratio (0.45 vs. 0.71 bilaterally). Supporting this, we observed several key differences in the relationship between external wrist measures compared to corresponding CT measures. Additionally, regression analyses combining participant factors and CT measurements produced models accounting for less than 15% of the variability in external wrist ratio (linear models) or correctly predicting less than 68% of wrist ratio-based risk categorization (logistic models). Overall, among healthy young adults, wrist shape is not an adequate proxy for CT shape.

KEYWORDS
anthropometric measurement, carpal tunnel, carpal tunnel syndrome, sonography, wrist ratio

1 | INTRODUCTION

Carpal tunnel syndrome (CTS) involves the focal compression of the median nerve within the carpal tunnel (CT) (Werner & Andary, 2002). CTS is highly prevalent and persistent among workers and within the general population (Dale et al., 2013; DeStefano et al., 1997; Feng et al., 2021; Luckhaupt et al., 2013), causing significant activity limitations (Cederlund et al., 2012), missed work days (Bureau of Labor Statistics. Nonfatal occupational injuries and illnesses requiring days away from work, 2020), and increased burden on the healthcare system (Elfar et al., 2012; Fernández-de-las-Peñas et al., 2019; Greenfield et al., 2021; Milone et al., 2019; Palmer & Hanrahan, 1995). Moreover, CTS involves considerable variability in its course, treatment, and outcomes (Baker et al., 2021; Baker & Livengood, 2014; DeStefano et al., 1997; Greenfield et al., 2021; Jenkins et al., 2013; Jerosch-Herold et al., 2017; Karjalanen et al., 2022), indicating the need for more precise identification of patient-specific etiology. Early identification, prevention, and targeted intervention for those at risk for CTS can avert the need for invasive and expensive surgical techniques (Barnes et al., 2021; Fernández-de-las-Peñas et al., 2019; Milone et al., 2019; Palmer & Hanrahan, 1995) and associated complications or side effects (Shi & MacDermid, 2011).

Wrist ratio (wrist palmodorsal depth/mediolateral width) is a powerful predictor of the development of CTS, with 'square-shaped' wrists (wrist ratio >0.7) developing CTS at a rate of three or more times that of those with smaller wrist ratios (Kamolz et al., 2004; Madani et al., 2022; Shiri, 2015; Thiese et al., 2017). Wrist ratio also may impact the outcomes of patients treated for CTS (Avsaroglu & Ozcakir, 2018). Despite being an external measure of the boney structure, wrist ratio has been suggested to be an adequate approximation of the internal CT shape (Chiotis et al., 2013), a potentially important factor in the mechanical compression of the median nerve in CTS.

Sonography is a valuable point-of-care tool for the treatment of musculoskeletal disorders (Shaikh et al., 2021). Sonographic imaging enables clinicians and researchers to visualize static and dynamic characteristics of otherwise inaccessible internal musculoskeletal structures, improving diagnostic accuracy, treatment monitoring, outcomes measurement, and precision treatment planning (Roll et al., 2015; Roll et al., 2016). While sonographic imaging has been used extensively to evaluate median nerve size and shape related to CTS (Erickson et al., 2022; Ng et al., 2022; Roll et al., 2011; Yao et al., 2020), it has rarely been used to explore the relationship between CT shape and development of CTS (Chiotis et al., 2013; Kamolz et al., 2004). Furthermore, there has been limited examination of the relationship between the external wrist shape and the internal CT shape (Chiotis et al., 2013). To our knowledge, no study has presented a detailed comparison between individual external wrist and multiple CT measures to explore and validate the assumed anthropometric association between these measures. Exploring sonographic assessment of CT shape and how external wrist shape relates to CT structure can inform more effective targeted preventative interventions, aid early CTS identification, and improve knowledge on variations in etiology.

Considering this, our study aimed to explore this relationship between external wrist ratio and sonographic CT measurements to (1) describe and evaluate the reliability of sonographic measurements of the CT and (2) explore how external wrist measures relate to anthropometric features of the CT. Because limited evidence exists, we conducted this study using a large sample of healthy young adults as a critical foundational step in understanding these measures and their relationship before attempting to develop applications or interpret findings in clinical populations.

2 | MATERIALS AND METHODS

2.1 | Participants and procedures

A cross-sectional observational study was completed with a convenience sample of asymptomatic students recruited from clinical healthcare programs at two universities between June 2015 and September 2018. The institutional review boards of both universities approved the study protocol, and informed consent was obtained from all study participants prior to data collection. Participants were excluded if they had a known history of CT release surgery, diagnosis of median nerve pathology, or any other history of trauma, surgery, or congenital condition that would alter the morphology of anatomical structures in the wrist region. Following enrollment, nerve conduction studies and clinical evaluations (e.g., provocative tests, Boston CT Questionnaire) were performed to confirm the absence of median nerve pathology. No other exclusion criteria were used.

Demographic data, including age, gender, hand dominance, and race/ethnicity, were self-reported by participants. Body mass index (BMI, kg/m (Feng et al., 2021)) was calculated from participants' height and weight measurements. External wrist width (mediolateral, mm) and depth (palmodorsal, mm) were measured by a single researcher [SCR] using a digital caliper at the distal wrist crease; these values were used to calculate external wrist ratio (depth/width). Sonographic imaging was performed by two sonographers, each with more than 10 years of experience, using a Logiq-e (GE Healthcare, Milwaukee, WI) ultrasound machine with a 12-MHz linear array transducer. During imaging, participants were seated facing the sonographer, with the shoulder adducted, elbow comfortably extended, forearm resting on the table in full supination, and hand relaxed. Transverse images of the CT were obtained at the level of the pisiform.

2.2 | Sonographic measures and reliability analysis

All transverse sonographic images were imported into ViewPoint version 6 (GE Healthcare) for post-processing review and measurement. The primary measures of CT cross-sectional area (CSA, mm (Feng et al., 2021)), width (mm), and depth (mm) were collected from pisiform-level images (Figure 1). CT CSA was calculated using a multipoint trace around the inner perimeter of the CT using the transverse carpal ligament and the proximal row of carpal bones as the boundary markers. CT width was measured as the distance between insertions of the transverse carpal ligament on the scaphoid and pisiform bones, and CT depth was measured as the length of the longest vertical line from the interior border of the transverse carpal ligament to the surface of the deep carpal bone. CT ratio was calculated by dividing CT depth by width. CT depth and width were collected via a single

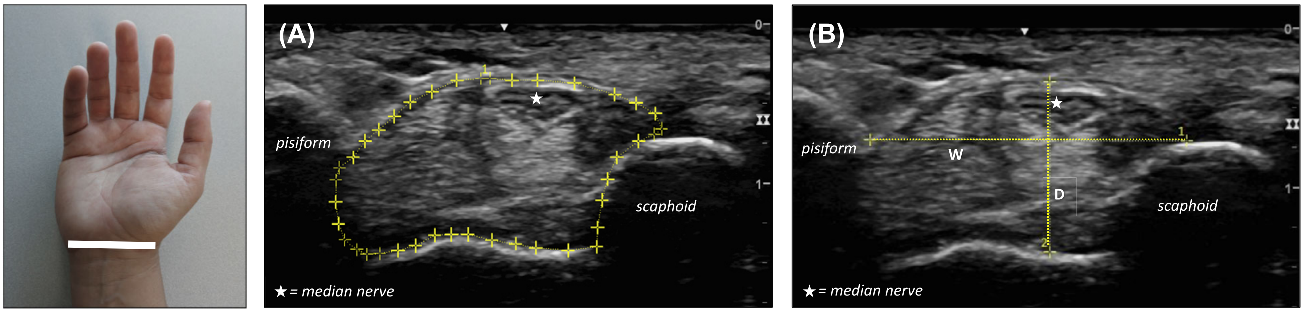

FIGURE 1 Carpal tunnel (CT) measures from cross-sectional sonographic images at the pisiform level. (A) CT cross-sectional area, calculated via tracing the inner perimeter of the CT using the transverse carpal ligament and proximal row of carpal bones as the boundaries. (B) CT width, measured as the distance between insertions of the transverse carpal ligament, and CT depth, measured as the longest vertical from the transverse carpal ligament to the deep carpal bone.

measurement, while CT CSA used an average of three successive measurements to minimize error.

Inter-rater reliability of each sonographic CT measure was assessed via intraclass correlation coefficient (ICC) between two raters on images from a random sample of 20 participants. ICC analyses used a two-way random model defined by absolute agreement based on single CT height and width measures and an average measure for CT CSA. ICC analyses were completed using SPSS version 28.0 (IBM Corp. Released 2021. IBM SPSS Statistics for Windows, ver.28.0. Armonk, NY: IBM Corp.). A single rater who participated in the reliability testing completed all measurements used in the descriptive and comparative analyses.

2.3 | Exploratory data analysis

Exploratory analyses were completed using SAS software version 9.4 (SAS Institute, Inc, Cary, NC), and $p < 0.05$ was considered statistically significant for comparative tests. As this was an anthropometric study, all data for an individual participant were excluded from analysis if any individual wrist or CT measurements were at least four standard deviations above or below the mean. Normality was assessed for continuous measures based on distribution skewness (>1.0) and kurtosis (>3.0), the Shapiro–Wilk test, and histogram and QQ plot appearance. Paired *t*-tests or Wilcoxon signed rank tests examined within-participant differences between dominant and nondominant measurements. Independent samples *t*-tests or Mann–Whitney *U* tests were used to investigate differences between genders, and analysis of variance (ANOVA) or Kruskal–Wallis tests were used to examine differences between races. Post-hoc pairwise tests used Scheffe's adjustments for ANOVA and Bonferroni corrections for Kruskal–Wallis tests.

Pearson's and Spearman's correlations (PROC CORR) were used to examine bivariate relationships among external wrist and sonographic CT measures. Next, regression analyses were conducted to determine if a combination of internal wrist structures and participant factors could adequately explain the external wrist ratio. Potential sonographic predictor variables considered for inclusion were CT depth, width, and CSA. Potential participant factors included age, race, BMI, and gender; all levels of categorical predictors were kept together for model selection. All eligible continuous predictor variables were centered (via mean), and those with correlations >0.60 were evaluated for collinearity using variance inflation factor (VIF) >10. Stepwise regression model selection (PROC GLMSELECT and PROC LOGISTIC, entry/exit cutoff of $p < 0.10$) was cross-referenced with best subsets regression (PROC REG and PROC LOGISTIC) to build linear and logistic regression models for dominant/nondominant wrist ratio and wrist ratio-based CTS risk categories (<0.7 vs. ≥ 0.7), respectively. Best subsets models were evaluated using adjusted *R* (Feng et al., 2021) and Mallow's C_p for linear models and correct classification percentage, Hosmer–Lemeshow goodness of fit, Akaike's information criterion (AIC), and Bayesian information criterion (BIC) tests for logistic models. The resulting regression models were evaluated for the need for statistical transformations via the distribution of residuals and plots of predicted versus residual values.

3 | RESULTS

We recruited and collected data from 228 participants; two were excluded from final analyses due to an extreme value in at least one measure (±4 standard deviations from the mean). The remaining 226 participants (Table 1) were predominantly female (86.7%), White or Asian (45.1%, 40.3%), right-handed (93.8%), with a mean age of 24.7 (SD: ±3.3) years, and a healthy BMI. For all exploratory analyses, race categories other than White or Asian were collapsed into a third group due to small sample sizes. Age and BMI were determined to be non-normally distributed and were analyzed using nonparametric tests for between-group and within-participant comparisons.

Reliability for all CT sonographic measures ranged from good to excellent (Koo & Li, 2016) for dominant and nondominant wrists (Table 2). The average values for all external wrist and internal sonographic CT measures are presented in Table 3. The mean CT ratios for dominant and nondominant wrists (0.45) were far lower than those of corresponding average wrist ratios (0.71). Using a wrist ratio threshold of ≥0.70 for risk classification, approximately two-thirds of

TABLE 1 Descriptive statistics of the healthy participant sample evaluated in this study ($n = 226$).

	Mean (SD) or frequency (%)
Age, years	24.7 (3.3)
BMI, kg/m^2	22.9 (3.9)
Gender, male	30 (13.3%)
Handedness, right	212 (93.8%)
Race	
American Indian/Alaska Native	2 (0.9%)
Asian	91 (40.3%)
Native Hawaiian or other Pacific Islander	1 (0.4%)
Black	4 (1.8%)
White	102 (45.1%)
Other	26 (11.5%)
Ethnicity, Hispanic	46 (20.4%)

Abbreviation: BMI, body mass index.

TABLE 2 Inter-rater reliability of sonographic carpal tunnel measures.

CT measure	Dominant ($n = 20$) ICC (95% CI)	Nondominant ($n = 20$) ICC (95% CI)
Height	0.88 (0.73–0.95)	0.95 (0.87–0.98)
Width	0.79 (0.54–0.91)	0.92 (0.80–0.97)
CSA	0.89 (0.73–0.96)	0.95 (0.88–0.98)

Abbreviations: CSA, cross-sectional area; CT, carpal tunnel; ICC, intraclass correlation coefficient.

TABLE 3 Mean (SD) for all external wrist and internal sonographic CT measures ($n = 226$).

	Dominant mean (SD)	Nondominant mean (SD)
Wrist ratio (depth/width)	0.71 (0.04)	0.71 (0.04)
Wrist depth (mm)	36.11 (2.97)	35.78 (2.98)
Wrist width (mm)	50.63 (3.51)	50.06 (3.42)
CT ratio (depth/width)	0.45 (0.06)	0.45 (0.06)
CT depth (mm)	10.33 (1.21)	10.28 (1.15)
CT width (mm)	23.25 (2.03)	22.80 (2.23)
CT CSA (mm^2)	191.03 (27.60)	186.70 (27.15)

Abbreviations: CSA, cross-sectional area; CT, carpal tunnel.

TABLE 4 Correlations among external wrist measures, internal sonographic CT measures, and combinations of the external and internal measures ($n = 226$).

	Dominant	Nondominant
External wrist–external wrist		
Wrist depth, wrist width	0.76**	0.77**
Wrist ratio, wrist depth	0.55**	0.58**
Wrist ratio, wrist width	−0.13	−0.08
CT–CT		
CT depth, CT width	0.11	0.08
CT ratio, CT depth	0.77**	0.74**
CT ratio, CT width	−0.54**	−0.60**
CT ratio, CT CSA	0.19*	0.12
CT CSA, CT depth	0.69**	0.65**
CT CSA, CT width	0.61**	0.62**
External wrist–CT		
Wrist depth, CT depth	0.33**	0.40**
Wrist depth, CT width	0.21*	0.15*
Wrist depth, CT ratio	0.15*	0.22*
Wrist depth, CT CSA	0.46**	0.40**
Wrist width, CT width	0.41**	0.35**
Wrist width, CT depth	0.41**	0.42**
Wrist width, CT ratio	0.08	0.10
Wrist width, CT CSA	0.61**	0.55**
Wrist ratio, CT ratio	0.13	0.20*
Wrist ratio, CT depth	−0.01	0.09
Wrist ratio, CT width	−0.21*	−0.21*
Wrist ratio, CT CSA	−0.08	−0.09

Abbreviations: CSA, cross-sectional area; CT, carpal tunnel.
*Significant at $p < 0.05$.**Significant at $p < 0.001$.

participants fell into the 'at risk' category for dominant ($n = 148$; 65.5%) and nondominant ($n = 153$; 67.7%) wrists. Variances of both wrist width and CT width exceeded those of the corresponding depth measurements, though the variance difference between width and depth was larger for CT measures than for wrist measures. That is, CT width variance was 2.8- and 3.7-times depth variance for dominant and nondominant wrists—more than double that of the corresponding external measures (i.e., width variance 1.4- and 1.3-times depth variance).

Minor differences were observed in nondominant wrist ratios and dominant CT depth (Cohen's $d = 0.39$, 0.47). While male participants exhibited larger measurements for both external wrist and sonographic CT measures, no significant difference between genders was detected for wrist or CT ratios. Between Asian and White participants, moderate effect size differences (Cohen's d between 0.50 and 0.65) were detected for dominant/nondominant wrist width, dominant/nondominant CT CSA, and nondominant CT depth.

Correlations between wrist and CT shape measures are detailed in Table 4. CT width and depth were moderately correlated with the external counterparts (0.33–0.41, $p < 0.001$); however, there was weak to no correlation between the external wrist ratio and internal CT ratio (dominant: $r = 0.12$, $p = 0.053$; nondominant: $r = 0.20$, $p = 0.002$). These results were not significantly altered when controlling for age, gender, race, or BMI. Wrist width was equivalently associated with both CT width and depth (dominant: 0.41; nondominant:

0.35–0.42), yet CT width and depth were not significantly correlated with each other. In contrast, wrist width and depth were strongly correlated. Furthermore, neither wrist ratio nor CT ratio was associated with CT CSA. Finally, CT width was strongly associated with CT ratio (dominant: −0.54; nondominant: −0.60), while wrist width was not associated with wrist ratio.

No collinearity was detected among potential internal measure predictors of carpal wrist shape (all VIFs ≤2.5). Among the final regression models (Figure 2), transformation of continuous variables did not significantly improve residual distributions or model fit. Additionally, no significant interactions were detected within the final models; therefore, no further adjustments were made to the final models. BMI was included in all final models, while race and CT width were included in three of the four final models. CT ratio replaced CT width in the nondominant logistic model. However, linear models only accounted for <15% of the variability of wrist ratio, and logistic models only correctly predicted participants' risk category <68% of the time (i.e., based on wrist ratio ≥0.70).

4 | DISCUSSION

We conducted a cross-sectional study of 226 healthy young adults to assess inter-rater reliability for basic sonographic measures of CT shape and to explore the relationship between external wrist shape and sonographic CT features, accounting for several demographic characteristics. Our results demonstrate good to excellent reliability between raters for basic sonographic measures of CT CSA, depth, and width, which builds upon previous findings establishing the validity (Kamolz et al., 2001; Shen & Li, 2012) and reliability (Bueno-Gracia et al., 2017; Gonzalez-Suarez et al., 2018; Kim et al., 2012; Shen & Li, 2012) of sonographic measurement of structural features of the CT. To our knowledge, our study is the first to report observed relationships among individual wrist and CT shape measurements beyond simple ratios. Importantly, our findings of limited associations between external wrist shape and internal CT shape raise questions about the validity of using external wrist measures as a proxy for internal anatomical features of the CT. Additionally, consideration of internal CT measures and personal demographics may help advance understanding of CT syndrome risk based on external wrist measures.

Our findings on the relationship between wrist ratio and CT ratio (dominant: 0.13, $p = 0.053$; nondominant: 0.20, $p = 0.002$) are numerically similar to Chiotis et al., 2013, who observed a correlation of 0.22 ($p = 0.054$) at the pisiform-level and 0.32 ($p = 0.002$) at the hamate-level of the CT. The weak overall correlation demonstrated within these two studies, as well as apparent differences in mean wrist and CT ratios (0.71 vs. 0.45 in our study, 0.68–0.71 vs. 0.42–0.56 in healthy controls of other studies) (Chiotis et al., 2013; Kamolz et al., 2004), suggests that external wrist shape is not necessarily a proxy or equivalent measure for CT shape. Furthermore, our finding of no association between wrist width and wrist ratio versus a strong association between wrist depth and wrist ratio (dominant 0.55; nondominant: 0.58) contradicts other studies on wrist ratio, which have identified wrist width as the primary contributor to differences in wrist shape (Madani et al., 2022; Ozcakir et al., 2018).

We observed several key indicators among the relationships of individual wrist and CT measures that help explain the lack of similarity between wrist and CT shapes (Figure 3). First, for dominant and nondominant wrists, there was greater variance in CT width than wrist width relative to corresponding depth measures (CT: width variance 2.8- and 3.7-times depth variance; wrist: width variance 1.4- and 1.3-times depth variance). Second, wrist width was equivalently associated with CT width and depth, while wrist depth was more strongly associated with CT depth than CT width. Additionally, counter to

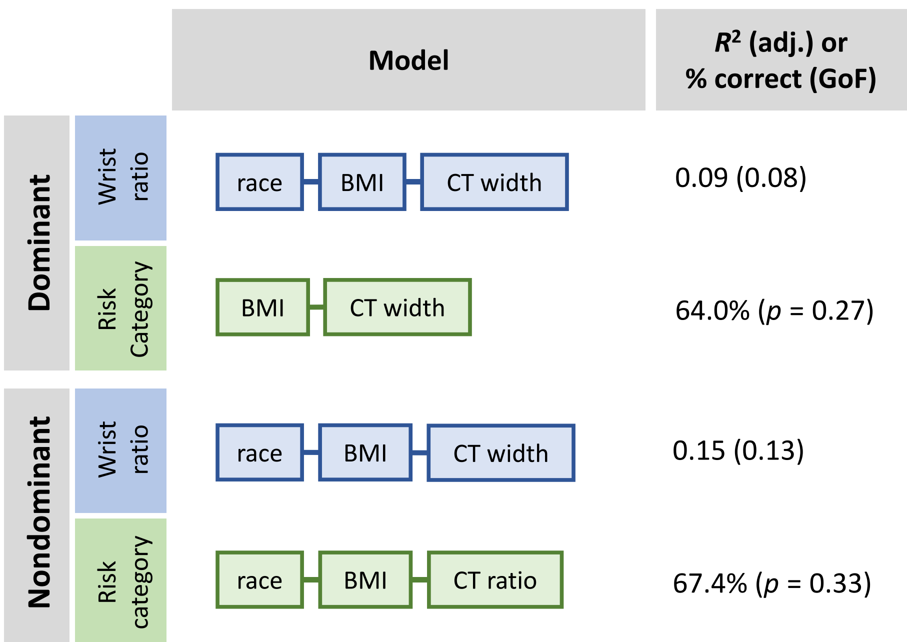

FIGURE 2 Final linear (blue) and logistic (green) regression models predicting dominant and nondominant external wrist shape, created by cross-referencing stepwise regression (entry/exit $p = 0.10$) and best subsets model selection. BMI, body mass index; CT, carpal tunnel; GoF, Hosmer Lemeshow goodness of fit test (nonsignificant p-value indicates acceptable fit).

Summary of Relationships Among Wrist and Carpal Tunnel (CT) Measures Contributing to Differences in Wrist and Carpal Tunnel Shape

- **Minimal to no correlation between wrist ratio and CT ratio**
- Greater variance for CT width vs. wrist width relative to corresponding depth measures
- Wrist width equally associated with CT width and depth, and wrist width at least equally associated with CT depth as wrist depth is associated with CT depth
- Wrist width and depth strongly correlated vs. CT width and depth not correlated
- CT width strongly associated with CT ratio vs. wrist width not correlated with wrist ratio

FIGURE 3 Observed relationships among external wrist and internal carpal tunnel (CT) measures that highlight the complexity of the relationship between wrist shape and CT shape and indicate the potential independence of these anthropometric measures relative to predicting risk for disease development.

expectations, wrist width was equally or more strongly associated with CT depth than wrist depth itself (wrist width vs. CT depth: 0.41, 0.42; wrist depth vs. CT depth: 0.33, 0.40) for dominant and nondominant wrists. Stated another way, wrist width seems to be the most strongly associated external measure with individual CT measures (width, depth); however, wrist width is not associated with CT ratio due to its equivalent associations with both CT width and depth. Conversely, wrist depth's differential association with CT width and depth (depth > width) produces a significant but small correlation with CT ratio (dominant: 0.15; nondominant: 0.22). Third, there appear to be differential relationships between wrist width and depth (strongly correlated at 0.76, 0.77) and their analogous CT measures (not correlated) for dominant and nondominant wrists. Fourth, CT width is strongly correlated with CT ratio (dominant: −0.54; nondominant: −0.60), yet wrist width is not associated with wrist ratio. Overall, the relationship between external wrist shape and internal CT shape seems far more complex than previously thought. Thus, when clinicians use wrist shape to assess the risk of CTS, they must be mindful that the outcome does not necessarily indicate compression or pathology related to CT shape, and in fact, the relationship between wrist shape and CTS risk continues to be ambiguous.

In our regression modeling, race, BMI, CT width, and CT ratio were identified as predictors of wrist ratio. However, the identified combinations of factors still did not sufficiently explain external wrist shape, as linear models represented <15% of wrist ratio variability and logistic models correctly predicted <68% of risk category assignment. These predictors should be considered highly preliminary due to the relaxed requirements of our model building. BMI has previously been found to have a weak to moderate relationship with wrist ratio (Hlebs et al., 2014; Kouyoumdjian et al., 2000; Palve & Palve, 2019) and to be an effect modifier of the relationship between wrist ratio and CTS (Thiese et al., 2017). Moreover, CT width demonstrated a stronger correlation with wrist ratio (−0.21, bilaterally) than did CT ratio or CT depth, possibly due to CT width's comparatively larger variance. Overall, the combination of basic health/demographic factors and measures of CT shape still do not adequately account for external wrist shape and therefore cannot be used to theoretically explain the relationship between wrist shape and CTS risk.

Wrist ratio (Kamolz et al., 2004; Madani et al., 2022; Shiri, 2015), CT ratio (Chiotis et al., 2013; Kamolz et al., 2004; Vögelin et al., 2014), and CT CSA (especially relative to median nerve CSA) (Kim et al., 2012; Li et al., 2011; Wessel et al., 2019) all have been previously linked to developing CTS, with significant differences in wrist and CT ratio observed between participants with CTS and controls. However, our data demonstrated little to no correlation between these three measures. This occurs not only because of the previously discussed differences between internal and external height and width but also because the CT is not a perfect ellipse, such that the CT ratio is also not a perfect approximation of the CT CSA. As such, all three of these measures may be independent risk factors for CTS rather than approximations or reflections of each other. Further exploration of the interrelationship or combined predictive validity of these factors among a sample of participants who have developed CTS would assist in understanding the interrelationship and predictive value of varied combinations of these factors. Combining the external measure of wrist ratio with sonographic measures of CT shape could provide more precise information on the risk and etiology of CTS than wrist ratio alone.

Finally, we note that the mean wrist ratio of our sample (0.71) was higher than healthy control participants of several other studies (0.67–0.70) (Hlebs et al., 2014; Kamolz et al., 2004; Kouyoumdjian et al., 2000; Lim et al., 2008; Moghtaderi et al., 2005; Mondelli et al., 2014; Ozcakir et al., 2018; Radecki, 1994; Radecki, 1995), resulting in a larger proportion of participants falling into the 'at risk' (≥0.7) category for CTS (66–68% vs. 44–48% in other studies) (Kouyoumdjian et al., 2000; Mondelli et al., 2014). The finding of average wrist ratios above the risk threshold in a healthy participant sample around 0.71 is not uncommon (Chiotis et al., 2013; Roll et al., 2011) and may result from differences in sample demographics. For example, we observed a significant difference in wrist width between White and Asian participants (dominant: 1.9 mm, nondominant: 2.2 mm, $p < 0.001$) within our sample. Unfortunately, we could not compare this finding or the distribution of race-based groups to other studies, as race differences or distributions for wrist ratio have not previously been reported. In addition, the mean age of our sample (25 years) was lower than the healthy control participants in other studies (43–54 years), such that those individuals with a higher wrist ratio may not yet have been exposed to other factors contributing to CTS. Although there were few males in our study ($n = 30$), we did not detect gender-based differences in wrist ratio as noted in previous studies (Moghtaderi et al., 2005; Radecki, 1994). It is also possible that the anatomical differences we observed between participants and between dominant/nondominant wrists were in part due to varying activity levels and usage of upper extremities over time, consistent with phenomena such as Wolff's Law (Frost, 1994). Overall, our data suggest there may be population-related differences in wrist ratio, which calls into question the conventional CTS risk threshold of 0.70.

Further investigation of the relationship between CTS risk, wrist shape, and demographic characteristics is needed.

4.1 | Limitations

Because of insufficient sample size in several race-based categories, all participants who were not White or Asian were combined into a third category of 'other.' Therefore, between-race comparisons were limited to White, Asian, and neither White nor Asian. The heterogeneity of this third group limits the ability to draw inferences regarding the impact of membership in that group on wrist and CT measures. Furthermore, our sample's relatively narrow demographics potentially limits external validity, and our limited sample of male participants may have prevented us from detecting sex-related anatomical differences. Additionally, many morphological studies of the CT examine cross-sectional features at the level of the hook of the hamate (Gabra et al., 2015). Our analysis was limited to pisiform-level cross-sectional images of the CT and does not necessarily generalize to other cross-sectional levels of the CT (e.g., the hook of the hamate); however, there is some evidence that width, depth, and CSA are similar throughout the length of the CT (Pacek et al., 2010). It is also possible that confounders such as varying activity levels or upper extremity usage contributed to anatomical differences, as these factors were not captured in our data collection.

Thus, our findings should be considered preliminary. Moreover, this study did not include participants diagnosed with CTS or follow participants longitudinally to monitor for CTS development. Therefore, within our sample, no conclusive inferences can be drawn on the direct relationship between wrist or CT shape and risk for CTS. Likewise, as the mean age of our sample was far younger than the age at which CTS typically develops, it is impossible to determine whether this asymptomatic sample is analogous to healthy controls in other studies investigating the relationship between wrist shape and risk for CTS.

5 | CONCLUSIONS

Basic sonographic measures of CT shape are reliable between raters. Overall, among young, healthy adults, there appears to be a different relationship between external wrist measures than between analogous CT measures, indicating that wrist shape is not a direct proxy for CT shape. Moreover, even when combined with other anatomical and demographic factors, basic CT dimensions do not adequately explain external wrist shape. Instead, wrist ratio, CT ratio, and CT CSA may be independent predictors of carpal CTS risk, though this requires confirmation among a sample that includes participants diagnosed with CTS. Future investigations on the relationship between wrist shape and CT features should examine additional CT characteristics (e.g., carpal bone or flexor tendon size, shape, and positioning). Finally, our data suggest that there may be population-related differences in wrist shape, which has implications for the validity of established CTS risk thresholds among different populations.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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REFERENCES

Avsaroglu, H., & Ozcakir, S. (2018). Effects of anthropometric measurements on treatment outcomes in patients with carpal tunnel syndrome. *The Journal of Hand Surgery (Asian-Pacific Volume)*, *23*(4), 528–532. https://doi.org/10.1142/S2424835518500534

Baker, N. A., Dole, J., & Roll, S. C. (2021). Meta-synthesis of carpal tunnel syndrome treatment options: Developing consolidated clinical treatment recommendations to improve practice. *Archives of Physical Medicine and Rehabilitation*, *102*(11), 2261–2268.e2. https://doi.org/10.1016/j.apmr.2021.03.034

Baker, N. A., & Livengood, H. M. (2014). Symptom severity and conservative treatment for carpal tunnel syndrome in association with eventual carpal tunnel release. *The Journal of Hand Surgery*, *39*(9), 1792–1798. https://doi.org/10.1016/j.jhsa.2014.04.034

Barnes, J. I., Paci, G., Zhuang, T., Baker, L. C., Asch, S. M., & Kamal, R. N. (2021). Cost-effectiveness of open versus endoscopic carpal tunnel release. *Journal of Bone and Joint Surgery American Volume*, *103*(4), 343–355. https://doi.org/10.2106/JBJS.19.01354

Bueno-Gracia, E., Malo-Urriés, M., Ruiz-de-Escudero-Zapico, A., Rodríguez-Marco, S., Jiménez-del-Barrio, S., Shacklock, M., Estébanez-de-Miguel, E., & Tricás-Moreno, J. M. (2017). Reliability of measurement of the carpal tunnel and median nerve in asymptomatic subjects with ultrasound. *Musculoskeletal Science and Practice*, *32*, 17–22. https://doi.org/10.1016/j.msksp.2017.08.001

Bureau of Labor Statistics. (2020). *Nonfatal occupational injuries and illnesses requiring days away from work*. US Department of Labor; 2021.

Cederlund, R. I., Dahlin, L. B., & Thomsen, N. O. (2012). Activity limitations before and after surgical carpal tunnel release among patients with and without diabetes. *Journal of Rehabilitation Medicine*, *44*(3), 261–267. https://doi.org/10.2340/16501977-0934

Chiotis, K., Dimisianos, N., Rigopoulou, A., Chrysanthopoulou, A., & Chroni, E. (2013). Role of anthropometric characteristics in idiopathic carpal tunnel syndrome. *Archives of Physical Medicine and Rehabilitation*, *94*(4), 737–744. https://doi.org/10.1016/j.apmr.2012.11.017

Dale, A. M., Harris-Adamson, C., Rempel, D., Gerr, F., Hegmann, K., Silverstein, B., Burt, S., Garg, A., Kapellusch, J., Merlino, L., Thiese, M. S., Eisen, E. A., & Evanoff, B. (2013). Prevalence and incidence of carpal tunnel syndrome in US working populations: Pooled analysis of six prospective studies. *Scandinavian Journal of Work, Environment & Health*, *39*(5), 495–505. https://doi.org/10.5271/sjweh.3351

DeStefano, F., Nordstrom, D. L., & Vierkant, R. A. (1997). Long-term symptom outcomes of carpal tunnel syndrome and its treatment. *The Journal of Hand Surgery*, *22*(2), 200–210.

Elfar, J. C., Foad, M. B., Foad, S. L., & Stern, P. J. (2012). A cost analysis of staged and simultaneous bilateral carpal tunnel release. *The Hand*, *7*(3), 327–332. https://doi.org/10.1007/s11552-012-9436-y

Erickson, M., Lawrence, M., & Lucado, A. (2022). The role of diagnostic ultrasound in the examination of carpal tunnel syndrome: An update and systematic review. *Journal of Hand Therapy*, *35*(2), 215–225. https://doi.org/10.1016/j.jht.2021.04.014

Feng, B., Chen, K., Zhu, X., Ip, W. Y., Andersen, L. L., Page, P., & Wang, Y. (2021). Prevalence and risk factors of self-reported wrist and hand symptoms and clinically confirmed carpal tunnel syndrome among office workers in China: A cross-sectional study. *BMC Public Health*, *21*(1), 57. https://doi.org/10.1186/s12889-020-10137-1

Fernández-de-las-Peñas, C., Ortega-Santiago, R., Díaz, H. F.-S., Salom-Moreno, J., Cleland, J. A., Pareja, J. A., & Arias-Buría, J. L. (2019). Cost-effectiveness evaluation of manual physical therapy versus surgery for carpal tunnel syndrome: Evidence from a randomized clinical trial. *Journal of Orthopaedic & Sports Physical Therapy*, *49*(2), 55–63. https://doi.org/10.2519/jospt.2019.8483

Frost, H. M. (1994). Wolff's law and bone's structural adaptations to mechanical usage: An overview for clinicians. *The Angle Orthodontist*, *64*(3), 175–188.

Gabra, J. N., Kim, D. H., & Li, Z.-M. (2015). Elliptical morphology of the carpal tunnel cross section. *European Journal of Anatomy*, *19*(1), 49–56.

Gonzalez-Suarez, C. B., Buenavente, L. D., Cua, R. C. A., Fidel, M. B. C., Cabrera, J. C., & Regala, C. F. G. (2018). Inter-rater and intra-rater reliability of sonographic median nerve and wrist measurements. *Journal of Medical Ultrasound*, *26*(1), 14–23. https://doi.org/10.4103/jmu.Jmu_2_17

Greenfield, P. T., Spencer, C. C., Dawes, A., Wagner, E. R., Gottschalk, M. B., & Daly, C. A. (2021). The preoperative cost of carpal tunnel syndrome. *The Journal of Hand Surgery*, *47*(8), 752–761.e1. https://doi.org/10.1016/j.jhsa.2021.07.027

Hlebs, S., Majhenic, K., & Vidmar, G. (2014). Body mass index and anthropometric characteristics of the hand as risk factors for carpal tunnel syndrome. *Collegium Antropologicum*, *38*(1), 219–226.

Jenkins, P. J., Srikantharajah, D., Duckworth, A. D., Watts, A. C., & McEachan, J. E. (2013). Carpal tunnel syndrome: The association with occupation at a population level. *Journal of Hand Surgery (European Volume)*, *38*(1), 67–72. https://doi.org/10.1177/1753193412455790

Jerosch-Herold, C., Houghton, J., Blake, J., Shaikh, A., Wilson, E. C., & Shepstone, L. (2017). Association of psychological distress, quality of life and costs with carpal tunnel syndrome severity: A cross-sectional analysis of the PALMS cohort. *BMJ Open*, *7*(11), e017732. https://doi.org/10.1136/bmjopen-2017-017732

Kamolz, L. P., Beck, H., Haslik, W., Högler, R., Rab, M., Schrögendorfer, K. F., & Frey, M. (2004). Carpal tunnel syndrome: A question of hand and wrist configurations? *Journal of Hand Surgery, British Volume*, *29*(4), 321–324. https://doi.org/10.1016/j.jhsb.2003.09.010

Kamolz, L. P., Schrögendorfer, K. F., Rab, M., Girsch, W., Gruber, H., & Frey, M. (2001). The precision of ultrasound imaging and its relevance for carpal tunnel syndrome. *Surgical and Radiologic Anatomy (English Ed)*, *23*(2), 117–121. https://doi.org/10.1007/s00276-001-0117-8

Karjalanen, T., Raatikainen, S., Jaatinen, K., & Lusa, V. (2022). Update on efficacy of conservative treatments for carpal tunnel syndrome. *Journal of Clinical Medicine*, *11*(4), 950. https://doi.org/10.3390/jcm11040950

Kim, H. S., Joo, S. H., Han, Z.-A., & Kim, Y. W. (2012). The nerve/tunnel index: A new diagnostic standard for carpal tunnel syndrome using sonography: A pilot study. *Journal of Ultrasound in Medicine*, *31*(1), 23–29. https://doi.org/10.7863/jum.2012.31.1.23

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting Intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine*, *15*(2), 155–163. https://doi.org/10.1016/j.jcm.2016.02.012

Kouyoumdjian, J. A., Morita, M. P. A., Rocha, P. R. F., Miranda, R. C., & Gouveia, G. M. (2000). Wrist and palm indexes in carpal tunnel syndrome. *Arquivos de Neuro-Psiquiatria*, *58*(3A), 625–629. https://doi.org/10.1590/s0004-282x2000000400005

Li, Z.-M., Masters, T. L., & Mondello, T. A. (2011). Area and shape changes of the carpal tunnel in response to tunnel pressure. *Journal of Orthopaedic Research*, *29*(12), 1951–1956. https://doi.org/10.1002/jor.21468

Lim, P. G., Tan, S., & Ahmad, T. S. (2008). The role of wrist anthropometric measurement in idiopathic carpal tunnel syndrome. *The Journal of Hand Surgery, European Volume*, *33*(5), 645–647. https://doi.org/10.1177/1753193408093326

Luckhaupt, S. E., Dahlhamer, J. M., Ward, B. W., Sweeney, M. H., Sestito, J. P., & Calvert, G. M. (2013). Prevalence and work-relatedness of carpal tunnel syndrome in the working population, United States, 2010 national health interview survey. *American Journal of Industrial Medicine*, *56*(6), 615–624. https://doi.org/10.1002/ajim.22048

Madani, A. M., Gari, B. S., Zahrani, E. M. A., Al-Jamea, L. H., & Woodman, A. (2022). A literature review of carpal tunnel syndrome and its association with body mass index, wrist ratio, wrist to palm ratio, and shape index. *Journal of Hand Therapy*, *36*(3), 568–579. https://doi.org/10.1016/j.jht.2022.03.002

Milone, M. T., Karim, A., Klifto, C. S., & Capo, J. T. (2019). Analysis of expected costs of carpal tunnel syndrome treatment strategies. *The Hand*, *14*(3), 317–323. https://doi.org/10.1177/1558944717743597

Moghtaderi, A., Izadi, S., & Sharafadinzadeh, N. (2005). An evaluation of gender, body mass index, wrist circumference and wrist ratio as independent risk factors for carpal tunnel syndrome. *Acta Neurologica Scandinavica*, *112*(6), 375–379. https://doi.org/10.1111/j.1600-0404.2005.00528.x

Mondelli, M., Aretini, A., Ginanneschi, F., Greco, G., & Mattioli, S. (2014). Waist circumference and waist-to-hip ratio in carpal tunnel syndrome: A case–control study. *Journal of the Neurological Sciences*, *338*(1), 207–213. https://doi.org/10.1016/j.jns.2014.01.012

Ng, A. J. T., Chandrasekaran, R., Prakash, A., & Mogali, S. R. (2022). A systematic review: Normative reference values of the median nerve cross-sectional area using ultrasonography in healthy individuals. *Scientific Reports*, *12*(1), 9217.

Ozcakir, S., Sigirli, D., & Avsaroglu, H. (2018). High wrist ratio is a risk factor for carpal tunnel syndrome. *Clinical Anatomy*, *31*(5), 698–701. https://doi.org/10.1002/ca.23198

Pacek, C. A., Tang, J., Goitz, R. J., Kaufmann, R. A., & Li, Z.-M. (2010). Morphological analysis of the carpal tunnel. *The Hand*, *5*(1), 77–81. https://doi.org/10.1007/s11552-009-9220-9

Palmer, D. H., & Hanrahan, L. P. (1995). Social and economic costs of carpal tunnel surgery. *Instructional Course Lectures*, *44*, 167–172.

Palve, S., & Palve, S. (2019). Study of wrist ratio and wrist-to-palm index radio in individuals suffering from carpal tunnel syndrome. *Annals of the Indian Academy of Neurology*, *22*(2), 159–163. https://doi.org/10.4103/aian.AIAN_343_18

Radecki, P. (1994). A gender specific wrist ratio and the likelihood of a median nerve abnormality at the carpal tunnel. *American Journal of*

Physical Medicine & Rehabilitation, *73*(3), 157–162. https://doi.org/10.1097/00002060-199406000-00003
Radecki, P. (1995). Variability in the median and ulnar nerve latencies: Implications for diagnosing entrapment. *Journal of Occupational and Environmental Medicine*, *37*(11), 1293–1299. https://doi.org/10.1097/00043764-199511000-00008
Roll, S. C., Asai, C., & Tsai, J. (2016). Clinical utilization of musculoskeletal sonography involving non-physician rehabilitation providers: A scoping review. *European Journal of Physical and Rehabilitation Medicine*, *52*(2), 253–262.
Roll, S. C., Evans, K. D., Li, X., Freimer, M., & Sommerich, C. M. (2011). Screening for carpal tunnel syndrome using sonography. *Journal of Ultrasound in Medicine*, *30*(12), 1657–1667. https://doi.org/10.7863/jum.2011.30.12.1657
Roll, S. C., Gray, J. M. L., Frank, G., & Wolkoff, M. (2015). Exploring occupational therapists' perceptions of the usefulness of musculoskeletal sonography in upper-extremity rehabilitation. *American Journal of Occupational Therapy*, *69*(4), 6904350020p1–6. https://doi.org/10.5014/ajot.2015.016436
Shaikh, S. Z., Tejashree, D., & Ajit, D. (2021). Clinical utility of ultrasonography imaging in musculoskeletal conditions: A systematic review and meta-analysis. *Journal of Medical Ultrasonics*, *48*(3), 285–294. https://doi.org/10.1007/s10396-021-01173-4
Shen, Z. L., & Li, Z.-M. (2012). Ultrasound assessment of transverse carpal ligament thickness: A validity and reliability study. *Ultrasound in Medicine & Biology*, *38*(6), 982–988. https://doi.org/10.1016/j.ultrasmedbio.2012.02.021
Shi, Q., & MacDermid, J. C. (2011). Is surgical intervention more effective than non-surgical treatment for carpal tunnel syndrome? A systematic review. *Journal of Orthopaedic Surgery and Research*, *6*(1), 17. https://doi.org/10.1186/1749-799x-6-17
Shiri, R. (2015). A square-shaped wrist as a predictor of carpal tunnel syndrome: A meta-analysis. *Muscle & Nerve*, *52*(5), 709–713. https://doi.org/10.1002/mus.24761
Thiese, M. S., Merryweather, A., Koric, A., Ott, U., Wood, E. M., Kapellusch, J., Foster, J., Garg, A., Deckow-Schaefer, G., Tomich, S., Kendall, R., Drury, D. L., Wertsch, J., Hegmann, K. T., & The Wistah Study Team. (2017). Association between wrist ratio and carpal tunnel syndrome: Effect modification by body mass index. *Muscle & Nerve*, *56*(6), 1047–1053. https://doi.org/10.1002/mus.25692
Vögelin, E., Mészàros, T., Schöni, F., & Constantinescu, M. A. (2014). Sonographic wrist measurements and detection of anatomical features in carpal tunnel syndrome. *The Scientific World Journal*, *2014*, 657906. https://doi.org/10.1155/2014/657906
Werner, R. A., & Andary, M. (2002). Carpal tunnel syndrome: Pathophysiology and clinical neurophysiology. *Clinical Neurophysiology*, *113*(9), 1373–1381. https://doi.org/10.1016/S1388-2457(02)00169-4
Wessel, L. E., Marshall, D. C., Stepan, J. G.-H., Sacks, H. A., Nwawka, O. K., Miller, T. T., & Fufa, D. T. (2019). Sonographic findings associated with carpal tunnel syndrome. *The Journal of Hand Surgery*, *44*(5), 374–381. https://doi.org/10.1016/j.jhsa.2018.07.015
Yao, B., Gan, K., Lee, A., & Roll, S. C. (2020). Comparing shape categorization to circularity measurement in the evaluation of median nerve compression using sonography. *Journal of Diagnostic Medical Sonography*, *36*(3), 224–232. https://doi.org/10.1177/8756479319898471

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