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Carpal arch and median nerve changes during radioulnar wrist compression in carpal tunnel syndrome patients

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Abstract

The purpose of this study was to investigate the morphological changes of the carpal arch and median nerve during the application of radioulnarly directed compressive force across the wrist in patients with carpal tunnel syndrome. Radioulnar compressive forces of 10 N and 20 N were applied at the distal level of the carpal tunnel in 10 female patients diagnosed with carpal tunnel syndrome. Immediately prior to force application and after 3 minutes of application, ultrasound images of the distal carpal tunnel were obtained. It was found that applying force across the wrist decreased the carpal arch width ($p < 0.001$) and resulted in increased carpal arch height ($p < 0.01$), increased carpal arch curvature ($p < 0.001$), and increased radial distribution of the carpal arch area ($p < 0.05$). It was also shown that wrist compression reduced the flattening of the median nerve, as indicated by changes in the nerve's circularity and flattening ratio ($p < 0.001$).

Statement of clinical significance—This study demonstrated that the carpal arch can be non-invasively augmented by applying compressive force across the wrist, and that this strategy may decompress the median nerve providing symptom relief to patients with carpal tunnel syndrome.

Keywords

carpal arch; carpal tunnel syndrome; compression; median nerve; wrist

Introduction

The carpal tunnel, enclosed by the carpal bones and the transverse carpal ligament (TCL), provides passage to the median nerve and flexor tendons. The tunnel affords limited space to its contents, and as a result the median nerve is vulnerable to compression. Chronic median nerve compression within the tunnel leads to the entrapment neuropathy known as carpal tunnel syndrome (CTS).

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Author Contributions Statement

TLM and ZML designed the experiment; TLM, PJE, and WHS recruited and screened study participants; TLM completed data acquisition; TLM and ZML participated in data analysis. All authors (TLM, PJE, WHS, and ZML) participated in data interpretation, clinical significance, and manuscript writing. All authors have read and approved of the final submitted manuscript.

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CTS is associated with morphological characteristics that are identifiable using imaging modalities such as magnetic resonance imaging and ultrasonography. Such imaging studies have shown that patients with CTS tend to have a smaller carpal tunnel cross-sectional area¹ and an increased bowing or outward convexity of the TCL.^{1–5} Median nerve morphological changes have also been reported in CTS patients, including increased nerve cross-sectional area^{2, 3, 6, 7} and increased nerve flattening,^{1–3} particularly at the distal carpal tunnel level. Many of these pathological features are thought to contribute to or be related to increased carpal tunnel pressure that is the hallmark of CTS.^{1, 8, 9}

Carpal tunnel release surgery is often performed for CTS patients to decompress the median nerve and reduce the elevated tunnel pressure.^{8, 10} The procedure involves transecting the TCL which results in morphological and positional changes in the carpal tunnel and its contents. After TCL transection, the cross-sectional area and volume of the tunnel increases^{11–14} as the edges of the transected TCL displace volarly.^{2, 11, 13–15} Furthermore, median nerve flattening is reduced^{1, 16} and the nerve displaces in the volar direction.^{2, 14} Although surgically releasing the TCL improves CTS symptoms, the invasive procedure disrupts the carpal tunnel structure and its native biomechanics^{11, 13, 14, 17, 18} which are thought to attribute to reduced grip strength and pillar pain postoperatively.

To avoid undesirable consequences associated with carpal tunnel release surgery, non-invasive approaches as potential alternatives have been investigated in an effort to relieve CTS symptoms. For example, techniques to widen the carpal arch width¹⁹ or stretch the TCL^{20–22} have been explored in an attempt to non-surgically increase carpal tunnel volume. However, a cadaveric study found that the TCL did not elongate when palmarly directed forces up to 200 N were applied directly to the ligament.²³ In contrast to approaches that aim to stretch the tunnel structure outward, it has been shown that applying compressive force across the wrist in the radioulnar direction may favorably augment the carpal tunnel space. This approach, which has been supported by modeling,²³ *in vitro*,^{23, 24} and *in vivo*⁴ studies, demonstrates that narrowing the carpal arch width (CAW) can increase the area within the carpal arch. An investigation into the effects of radioulnar wrist compression in healthy, female adults revealed that the median nerve also undergoes morphological and positional changes similar to those demonstrated by CTS patients after carpal tunnel release surgery.⁴ However, the effects of applying compressive force across the wrists of CTS patients have not been examined.

Therefore, the purpose of this study was to investigate the morphological changes of the carpal arch and median nerve associated with applying radioulnar compressive force across the wrists of patients with CTS. It was hypothesized that the applied force would decrease CAW, and increase carpal arch curvature and area. Furthermore, it was hypothesized that the compressive force would decrease the flattening of the median nerve.

Methods

This was a Level II evidence prospective comparative study. The study was approved by the institutional review board and patients provided written, informed consent prior to study participation.

2.1 Human subjects

Patients diagnosed with CTS voluntarily participated in this study (n=10; female, 8 right hands and 2 left hands; 54.4 ± 7.6 years old). Each patient was clinically diagnosed with CTS based on a history of paresthesias, pain and/or numbness in the median nerve innervated hand territory persisting for at least three months, positive provocative maneuvers (e.g. Phalen's test, Tinel's sign, and/or median nerve compression test), and a mean CTS Severity Score of greater than 1.5.²⁵ Patients were excluded from participation if they had a history of injury, surgical intervention, or musculoskeletal/neuromuscular disorders affecting the hand/wrist in addition to CTS, or if they had a systemic disease commonly associated with increased incidence of CTS (e.g. diabetes, rheumatoid arthritis, fibromyalgia).

2.2 Experimental procedures

Radioulnar compressive forces were applied across the wrists of the CTS patients using a custom compression system that has been previously described.⁴ In brief, the system applied force using two pneumatic actuators (Bimba Manufacturing, Monee, IL, USA) that were fitted with custom end effectors to accommodate the natural curvature of the hand/wrist. The end effectors were molded from thermoplastic material, and the surface of each end effector that made contact with the wrist was covered with a thin piece of foam (0.3 cm thick). The same pair of end effectors was used for all patients in this study. An air pressure regulator (VBM Medical, Noblesville, IN, USA) with bifurcated tubing drove the pneumatic actuators according to a predetermined calibration that related the amount of regulator pressure to the amount of force applied by the actuators.

Each participant laid supine on a testing bed with the arm abducted 60° and the hand resting with the palm facing up on the compression system. A Velcro® strap was used to secure the forearm. A finger restraint stabilized the four fingers in extension and the thumb was secured in a naturally abducted position with a Velcro® strap. An ultrasound system (Acuson S2000, Siemens Medical Solutions USA, Mountain View, CA, USA) with an 18L6 HD linear array probe (Siemens Medical Solutions USA, Mountain View, CA, USA) was used to identify the axial imaging plane that clearly contained the hook of the hamate and ridge of the trapezium, corresponding to the distal level of the carpal tunnel. The footprint of the ultrasound probe was outlined on each patient's skin using a marking pen. Then, the actuators of the compression system were aligned so that the end effectors' line of action coincided with the outlined ultrasound probe's footprint. The end effectors were further adjusted to ensure that the center of each end effector was positioned at the mid-point between the volar and dorsal aspects of the wrist (Figure 1).

Radioulnar, compressive forces of 10 N and 20 N were applied across the wrist for each patient. Each force level was applied a total of four times and the order of force application was randomized for each patient. At the beginning of each trial, the ultrasound probe was oriented perpendicularly to the patient's palm to obtain an axial imaging plane that contained the hook of the hamate, ridge of the trapezium, median nerve, and the thenar muscles' ulnar point.²⁶ The outlined footprint of the ultrasound probe was used to guide the probe's orientation. Then, three ultrasound images were captured at the distal carpal tunnel level without force application (unloaded, 0 N condition). Next, the compression system

generated and applied the predetermined force across the wrist for 3 minutes. After 3 minutes of continuous compression, three additional ultrasound images were taken of the distal carpal tunnel following the above described probe positioning procedure. After each trial, the compressive force was removed and the patient was given a 5-minute rest between consecutive trials. Throughout the experiment, the ultrasound system was operated in two-dimensional B-mode with tissue harmonic imaging at a frequency of 8–12 MHz, a gain of 0–10 dB, and an image depth of 2.5 cm. Care was taken to minimize the amount of force applied to the skin by the ultrasound probe through the maintenance of a gel layer (about 5 mm). Additionally, the experimenter ensured that the probe was perpendicular to palm of the subject during imaging in order to prevent parallax error of the morphological outcomes.

2.3 Data analyses

One trial of each force magnitude (10 N and 20 N) was used for analyses for each patient; the remaining trials were used as backup. The trial analyzed was selected based on the image quality that best depicted the targeted landmarks of interest, i.e. hook of the hamate, ridge of the trapezium, thenar muscles, TCL, and median nerve. For each trial, the three unloaded images (0 N condition) and the three loaded images (10 N or 20 N condition) were examined by a single investigator (TLM) who was trained in ultrasound imaging. The examiner was blinded to the magnitude of applied force in each image. Using the *ImageJ* point tool (US National Institutes of Health, Bethesda, MD, USA), the coordinates of the most volar aspect of the hook of the hamate and the ridge of the trapezium, as well as the thenar muscles' ulnar point, were determined on each image. Then, the coordinates of the volar boundary of the TCL were found by manual selection using the *ImageJ* segmented line tool.

The border of the median nerve was manually selected and the coordinates of the nerve's centroid were determined using the *ImageJ* polygon selection tool. Shape descriptors of the median nerve, specifically its perimeter, area, circularity, and flattening ratio, were quantified based on the nerve tracing using the measure function in *ImageJ*. Circularity ($4\pi * \frac{\text{area}}{\text{perimeter}^2}$) and flattening ratio ($\frac{\text{major axis}}{\text{minor axis}}$ of fit ellipse) are complementary indicators of the nerve's roundness, where a value of 1.0 for both parameters represents a perfect circle. The more flattened the shape, the closer its circularity is to 0 and its flattening ratio approaches infinity. At the time of data collection, it was discovered that one study participant had a bifurcated median nerve at the distal tunnel level. For this patient, the larger of the two portions of the median nerve was used in the analyses. To prevent any potential bias that this may introduce, the nerve's perimeter and area measurements for each participant were normalized by their respective values at the 0 N condition.

A custom *MATLAB* (MathWorks, Natick, MA, USA) program was used to transform the coordinates obtained in *ImageJ* to an anatomical coordinate system. The origin of the anatomical coordinate system was located at the ridge of the trapezium and the x-axis was defined as the line that passed through the points representing the trapezium and the hook of the hamate, pointing in the ulnar direction. The y-axis was perpendicular to the x-axis and pointed volarly.

The *MATLAB* program also calculated morphological outcome parameters of the carpal arch. CAW was defined as the distance between the ridge of the trapezium and the hook of the hamate points. Carpal arch height (CAH) was the perpendicular distance from the thenar muscles' ulnar point to the line connecting the ridge of the trapezium and the hook of the hamate (i.e. CAW line). To determine carpal arch curvature (CAC), the volar boundary of the TCL was least-squares fitted to a circle¹⁵ and CAC was determined as the inverse of the radius of the fitted circle. The total carpal arch area (CAA) was calculated as the area bounded by the volar TCL boundary and the CAW line.¹⁵ Furthermore, the distribution of CAA within the radial portion of the carpal arch was determined. This distribution, radial carpal arch area (rCAA), was calculated as the percentage of CAA from the ridge of the trapezium to the midpoint of the CAW at 0 N.

2.4 Statistical analysis

Data were averaged for each patient across the representative images for each specific force magnitude and respective outcome parameter. One-way repeated measures ANOVAs were used with the independent variable of force magnitude (0 N, 10 N, and 20 N) and dependent variables of the carpal arch (CAW, CAH, CAC, CAA, and rCAA) and the median nerve (perimeter, area, flattening ratio, circularity, and centroid location). Post-hoc Tukey's tests were used for all pairwise comparisons. Statistical analyses were performed using SigmaStat 3.5 (Systat Software Inc, San Jose, CA, USA) and a $p < 0.05$ was considered statistically significant.

Results

The application of radioulnar, compressive force across the distal level of the carpal tunnel resulted in morphological changes to the carpal arch and median nerve, as captured in ultrasound images (Figure 2). In comparison to the 0 N condition, the carpal arch narrowed and the curvature of the TCL increased when force was applied across the wrist. Similarly, the median nerve shape became more round with the compressive force application (Figure 3).

Force application across the wrist significantly affected CAW ($p < 0.001$), CAH ($p < 0.01$) and CAC ($p < 0.001$). CAW decreased by 1.0 ± 0.5 mm with 10 N of applied force and by 1.6 ± 0.9 mm with 20 N of force, relative to the initial CAW of 22.9 ± 1.7 mm at the 0 N condition (Figure 4). Pairwise comparisons revealed significant differences between CAW at 0 N vs. 10 N ($p < 0.001$), 0 N vs. 20 N ($p < 0.001$), and 10 N vs. 20 N ($p < 0.05$). CAH increased with force application from 2.1 ± 0.7 mm at 0 N to 2.4 ± 0.9 mm at 10 N and 2.6 ± 0.9 mm at 20 N. There was a significant difference between CAH at 0 N vs. 20 N ($p < 0.01$), but not for the remaining pairwise comparisons. CAC at the initial 0 N condition was 0.029 ± 0.011 mm⁻¹, and it changed to 0.034 ± 0.013 mm⁻¹ at 10 N and 0.037 ± 0.013 mm⁻¹ at 20 N. The difference between CAC at 0 N and 10 N, as well as 0 N and 20 N were statistically significant ($p < 0.05$).

Despite changes in the other carpal arch parameters, CAA was not significantly affected by force ($p = 0.078$), remaining relatively constant (31.6 ± 9.9 mm² at 0 N) with application of increasing compressive force (35.7 ± 11.9 mm² at 10 N and 35.0 ± 14.6 mm² at 20 N).

However, further analysis of the distribution of the area within the carpal arch revealed a radial shift of CAA with increasing compressive force; rCAA was significantly affected by force application ($p < 0.05$). At 0 N, rCAA was $45.1 \pm 7.5\%$ and rCAA increased to $50.0 \pm 5.8\%$ at 10 N and $52.3 \pm 6.8\%$ at 20 N. Pairwise analyses revealed a significant difference between 0 N and 20 N ($p < 0.05$) for rCAA.

Morphological changes of the median nerve were also found when force was applied across the wrist. At the 0 N condition, the nerve's perimeter was 16.7 ± 2.2 mm and its area was 11.3 ± 2.7 mm². At 10 N and 20 N, the nerve's perimeter was decreased to $93.0 \pm 5.9\%$ and $91.0 \pm 6.0\%$ of its initial value, respectively. Pairwise comparisons revealed significant differences between the perimeter for the 0 N vs. 10 N ($p < 0.01$) and the 0 N vs. 20 N ($p < 0.001$) conditions. Although the nerve's perimeter was affected, force application did not significantly change the nerve's area ($p=0.344$).

Displacement of the nerve's centroid also occurred; however, inter-patient centroid displacement was variable relative to its 0 N location, ranging from 0.2–2.2 mm at 10 N and 0.5–3.6 mm at 20 N relative. Average displacement of the nerve centroid across patients was 0.9 ± 0.7 mm at 10 N ($p < 0.01$) and 1.6 ± 1.1 mm at 20 N ($p < 0.001$) relative to its 0 N location. The majority of patients had centroid displacements predominantly in the radial direction.

Both roundness parameters of the median nerve (circularity and flattening ratio) showed that the nerve became rounder as the applied force increased (Figure 5). The applied force significantly affected the nerve's circularity ($p < 0.001$); it increased from 0.51 ± 0.11 at 0 N to 0.60 ± 0.12 at 10 N and 0.64 ± 0.11 at 20 N. Similarly, the flattening ratio was significantly affected by force ($p < 0.001$). The initial flattening ratio of the nerve was 4.36 ± 1.52 , and it decreased to 3.43 ± 1.02 at 10 N and 3.08 ± 0.86 at 20 N. Post-hoc analyses showed pairwise differences between 0 N vs. 10 N ($p < 0.001$) and 0 N vs. 20 N ($p < 0.001$) for both the median nerve's circularity and flattening ratio.

Discussion

In this study, compressive forces were applied across the carpal tunnel in patients with CTS, and the corresponding changes in the carpal arch and median nerve morphologies were quantified from ultrasound images. Compressive force applied across the wrist decreased CAW and increased CAH, CAC, and rCAA. Within the tunnel, the median nerve's shape parameters indicated that the nerve became rounder when force was applied across the wrist.

Previous studies have investigated the morphology of the carpal tunnel and its contents in patients with CTS. Relative to control subjects, CTS patients often display increased palmar bowing of the TCL, as well as increased median nerve cross-sectional area and flattening.^{1–3} In the current study, CAH was used to quantify the palmar bowing of the TCL. In comparison to our previous study with control subjects, the initial CAH was greater for the CTS patients (2.1 mm) than for the controls (1.2 mm).⁴ This finding is consistent with previous studies although the magnitude of bowing in our study was less than formerly reported for patients.^{1, 3}

In the current study, the CTS patients had a median nerve cross-sectional area of 11.3 mm² which agrees well with previous studies that have reported nerve enlargement in CTS patients.^{1, 27} Of note, this average nerve area was somewhat underestimated due to the fact that one patient had a bifurcated median nerve and only the large branch was used for the analyses. The patients in this study also had greater initial flattening of the median nerve in comparison to control subjects previously examined using the same experimental methods.⁴ The flattening ratio of the nerve was approximately 4.4, which is less than the ratios of 5.1¹ and 5.6³ previously reported for patients with CTS. This difference may be attributable to variations in CTS severity or methodologies across the studies.

This study further demonstrated that CAW can be non-invasively narrowed *in vivo* by applying compressive forces across the wrist. The magnitude of narrowing achieved with 20 N of compressive force was 1.6 mm which is in accordance with the amount of narrowing achieved in healthy controls with the same experimental protocol.⁴ Even though force application led to decreases in CAW and increases in CAH and CAC, CAA was relatively unchanged. This may be attributable to the initial bowing of the TCL in CTS patients. The greater the initial CAH, the smaller the expected increases in CAH and CAA from CAW narrowing.²⁴

Further examination of CAA revealed that its distribution within the carpal arch became radially skewed during force application although total area was not changed. The redistribution of area within the carpal arch and increased CAC likely were associated with the morphological changes of the median nerve. The configuration of the carpal tunnel contents have been shown to adjust their shape and location depending on space-availability within the tunnel;^{11, 14, 28} it has been shown that the nerve displaces and undergoes shape changes to minimize insult within the tunnel space.²⁹ The application of compressive force across the wrist resulted in a rounder median nerve, as indicated by its increased circularity and decreased flattening ratio. These changes agree well with our previous study in asymptomatic subjects.⁴ As the median nerve shape changed, it also had centroid displacement. The centroid displacement in the current patient study was more variable than that in asymptomatic subjects.⁴ Prior studies have shown that patients with CTS display different median nerve displacement patterns during finger motion than controls,^{30–32} including a reduction in volar displacement.³⁰ The nerve changes in this study are likely related to increased CAC and rCAA which reconfigured the space within the carpal arch permitting shifting of the carpal tunnel contents within the tunnel. Therefore, increasing the rCAA for CTS patients may be beneficial in providing symptom relief because more space was made available in the proximity of the median nerve in the carpal tunnel.

The changes in the median nerve shape during radioulnar wrist compression are similar to changes observed after carpal tunnel release surgery. For example, the notable flattening of the median nerve at the distal level of the carpal tunnel in CTS patients^{1–3} is reduced and approaches normative levels following carpal tunnel release surgery.^{1, 16, 33} In the present study, during radioulnar wrist compression the median nerve's flattening also decreased. Future studies are warranted to investigate if such median nerve morphological changes associated with radioulnar wrist compression improve symptoms in CTS patients.

We acknowledge that this study has limitations to consider when interpreting its results. First, CTS severity was not included as a factor in this study; most patients were identified to have mild to moderate CTS severity (average CTS Severity Score of 2.6, range: 1.6–3.9). The presence of more mild CTS may explain the less pronounced flattening of the median nerve in the initial, unloaded condition. Second, only female patients were recruited to eliminate any potential gender effects. Future studies may explore the effects of CTS severity and gender on the results of radioulnar wrist compression. Third, only the morphological changes of the volar portion of the carpal tunnel (carpal arch) were quantified. Ultrasound provides clear visualization of the carpal arch, but visualizing the dorsal tunnel boundaries can be challenging due to penetration limitations and shadowing from bony structures. It is possible that changes to the dorsal tunnel boundary or shifting of the flexor tendons may have also contributed to the findings of this study. Finally, the exact amount of force applied to the hamate and trapezium at the distal tunnel is unknown; it is likely that there was some force dissipation to the soft tissues surrounding the wrist during experimentation.

This study showed that the carpal arch can be biomechanically manipulated to potentially decompress the median nerve in CTS patients. An initial force application strategy was used in this study to demonstrate the feasibility of this therapeutic option. It is likely that greater effects from biomechanical manipulation of the carpal arch may be achieved with the identification of an optimum compression approach that refines the applied force. Furthermore, the treatment dosage (e.g. duration and frequency of force application) is in need of future investigation to maximize therapeutic effects such as pain relief.

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Figure 1.
The experimental setup with the compression system aligned and the location of ultrasound imaging indicated.

Figure 2.

Ultrasound images at 0 N, 10 N, and 20 N of force application for a representative patient with the bottom row of images including identified landmarks of interest: hook of the hamate (HH), ridge of the trapezium (TM), thenar muscles' ulnar point (TUP), volar boundary of the TCL (solid line), and median nerve (outline).

Figure 3.

Configurations of the carpal arch and anatomical landmarks during different force conditions for a representative subject. Marked symbols are for the hook of hamate (■), thenar muscles' ulnar point (▲), volar boundary of the transverse carpal ligament (dashed line), median nerve (solid line), and nerve's centroid (●).

Figure 4.
The carpal arch width (CAW) at compressive force magnitudes of 0 N, 10 N, and 20 N. * $p < 0.05$, *** $p < 0.001$

Figure 5. Representative outlines of the median nerve for each patient at the different magnitudes of compressive force (0 N, 10 N, and 20 N) with the black dashed line indicating the average fit ellipse across all patients.