Ultrasound Assessment of the Displacement and Deformation of the Median Nerve in the Human Carpal Tunnel with Active Finger Motion

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Background: Peripheral nerves are mobile structures, stretching and translating in response to changes in the position of adjuvant anatomic structures. The objective of this study was to develop a novel method to characterize the relative motion and deformation of the median nerve on cross-sectional ultrasound images of the carpal tunnel during active finger motion.

Methods: Fifteen volunteers without a history of carpal tunnel syndrome or wrist trauma were recruited. An ultrasound scanner and a linear array transducer were used to evaluate the motion of the median nerve and the flexor tendons within the carpal tunnel during motion from full extension to full flexion by the four fingers (fist motion) and by the long finger alone. The displacement of the median nerve relative to the long-finger flexor digitorum superficialis tendon as well as the perimeter, cross-sectional area, circularity, and aspect ratio of a minimum enclosing rectangle of the median nerve were measured. The data were compared between single-digit motion and fist motion and between extension and flexion positions.

Results: The distance between the long-finger flexor digitorum superficialis tendon and the median nerve with isolated long-finger flexion was decreased in the ulnar-radial direction and increased in the palmar-dorsal direction as compared with the distance with four-finger flexion ($p < 0.01$). Compared with the values with fist motion, the aspect ratio was decreased and the circularity was increased with long-finger motion ($p < 0.01$).

Conclusions: This report presents a method with which to assess displacement and deformation of the median nerve on a cross-sectional ultrasound image during different finger motions. This method may be useful to assess pathological changes within the carpal tunnel, and we plan to perform a similar study of patients with carpal tunnel syndrome on the basis of these preliminary data.

Level of Evidence: Diagnostic Level IV. See Instructions to Authors for a complete description of levels of evidence.

Peripheral nerves are mobile structures, stretching and translating in response to changes in the position of nearby joints, muscles, and tendons¹⁻³. The gliding interface between nerves and adjacent tissues is an important physiological phenomenon that is essential to minimize traction and compression of the nerves in response to movement of the extremity⁴. In contrast, in the setting of chronic nerve compression, fibrosis in the surrounding connective tissues hinders nerve gliding and results in localized stretch or compression that may exceed the nerve's physiological capacity and result in nerve dysfunction⁵⁻⁷.

Carpal tunnel syndrome is a well-known chronic compression neuropathy. Although the clinical aspect of this disease has been well studied, its cause remains unknown^{8,9}. Changes in mechanical properties and fibrosis of the sub-synovial connective tissue within the carpal tunnel are the major pathological findings in patients with carpal tunnel syndrome^{10,11}. Although these changes may hinder median-nerve gliding¹² and lead to elevated local strains and pressures, so far there is no way to diagnose the cause of this condition.

Although other studies are more commonly used to confirm the diagnosis of carpal tunnel syndrome and exclude

Disclosure: In support of their research for or preparation of this work, one or more of the authors received, in any one year, outside funding or grants in excess of \$10,000 from National Institutes of Health/National Institute of Arthritis and Musculoskeletal and Skin Diseases Grant AR49823. Neither they nor a member of their immediate families received payments or other benefits or a commitment or agreement to provide such benefits from a commercial entity.

other pathological conditions^{13,14}, diagnostic ultrasonography is an attractive modality. Diagnostic ultrasound equipment is widely available, the cost of soft-tissue ultrasound is usually less than that of other soft-tissue imaging modalities, the equipment is portable, and it allows both static and dynamic imaging. In addition, the development of high-resolution ultrasound imaging has increased our capability to evaluate the structures within the carpal tunnel, and static cross-sectional ultrasound imaging of the carpal tunnel has been proposed as an adjunct for the diagnosis of carpal tunnel syndrome¹⁵⁻¹⁸.

Static ultrasonography can detect pathological changes such as thickening and alteration of the echogenicity of the flexor tendons¹⁹ and flexor retinaculum²⁰, synovial proliferation, swelling of the median nerve in the proximal part of the carpal tunnel, and flattening of the median nerve in the carpal tunnel^{15-17,21}. Also, reduced longitudinal gliding of the median nerve at the wrist has been demonstrated in patients with carpal tunnel syndrome^{12,22,23}. Although these findings may distinguish patients with carpal tunnel syndrome from normal subjects, there have been few attempts to detect the progression or risk of carpal tunnel syndrome on the basis of ultrasound images or to consider the three-dimensional movement of the tendons and nerve.

The objective of this study was to develop a novel method with which to characterize the relative motion and deformation of the median nerve on cross-sectional ultrasound images of the carpal tunnel during finger motion, so that ultimately simultaneous longitudinal and cross-sectional motion can be combined to construct four-dimensional maps

(three-dimensional ultrasound images viewed dynamically in time) of tendon and nerve movement, which may aid in the understanding of the pathology of carpal tunnel syndrome. Our null hypothesis was that we would find no difference in the cross-sectional motion or shape of the median nerve when we compared two finger-movement conditions.

Materials and Methods

This study protocol was approved by our institutional review board. Fifteen asymptomatic volunteers (eight male and seven female), with a mean age (and standard deviation) of 35 ± 8 years, were recruited. Individuals were excluded if they reported a history of carpal tunnel syndrome, cervical radiculopathy, rheumatoid arthritis, osteoarthritis, degenerative joint disease, flexor tendinitis, gout, hemodialysis, sarcoidosis, peripheral nerve disease, amyloidosis, hypothyroidism, or traumatic injuries to the hand, wrist, or forearm or if they had hand pain or numbness.

Participants were given a brief description of the purpose of the research and the testing procedures during the initial contact. All participants provided verbal informed consent, which our institutional review board had determined was sufficient for this minimal risk study.

Image Acquisition Procedure

Each participant was imaged while lying supine with the shoulder abducted to 45° , the elbow fully extended, and the forearm supinated. The forearm was secured to a custom-made table with the wrist in the neutral position (Fig. 1). An

Fig. 1

Setup for ultrasound examination. 1 = rubber band to secure the hand, 2 = protractor, 3 = transducer, 4 = transducer holder, 5 = adjustable arm.

Fig. 2-A

Fig. 2-B

Fig. 2-C

Figs. 2-A, 2-B, and 2-C Image analysis of the median nerve. **Fig. 2-A** Cross-sectional image of the carpal tunnel in finger extension. FDS = flexor digitorum superficialis. **Fig. 2-B and Fig. 2-C** Aspect ratio of the minimum enclosing rectangle (Fig. 2-B) and circularity (Fig. 2-C). P = nerve perimeter, A = nerve area.

ultrasound scanner (Acuson Sequoia C512; Siemens Medical Solutions, Malvern, Pennsylvania) equipped with a 15L8 linear array transducer was set to a depth of 20 mm with a 14-MHz image acquisition frequency. Ultrasound evaluation was performed by an orthopaedic surgeon trained in the image acquisition procedure.

The image acquisition frame rate was maintained at 70 Hz, and the image compression was set to low. The transducer was placed at the level of the wrist crease (the proximal part of the carpal tunnel) with the wrist in the neutral position. To minimize compression of the carpal tunnel contents, the transducer was applied to the skin without additional pressure. The

Fig. 3

Tendon and nerve displacement. a: Total displacement of the tendon was significantly larger with fist motion than it was with long-finger motion ($p = 0.018$). b: The tendon moved in an ulnar direction with fist motion and in a radial direction with isolated long-finger motion. There were significant differences in ulnar-radial motion of the tendon between the fist and long-finger motions ($p < 0.01$). c: The tendon moved in a palmar direction with fist motion and in a dorsal direction with long-finger motion. There was a significant difference in palmar-dorsal motion of the tendon between the fist and long-finger motions ($p < 0.01$). The I-bars indicate the standard deviation.

transducer was maintained perpendicular to the surface skin of the wrist crease with reference to a protractor attached to the table. In addition, the transducer direction was set so that the ulnar side of the wrist was seen on the right side of the monitor.

The median nerve and the long-finger flexor digitorum superficialis tendon were identified by cross-sectional and longitudinal ultrasonographic imaging during flexion and extension of the long finger. The participants were asked to flex and extend all four fingers (index, long, ring, and little) as a fist motion or to flex the long finger independently as a single-digit motion. When the subjects flexed only the long finger, they actively held the other three fingers in extension. The participants were asked to move from full finger extension (0° at each finger joint) to maximum flexion (i.e., until the fingertip touched the palm). They were also asked to move the finger(s) continuously and repeatedly, with a metronome marking a beat of 0.8 Hz for each direction of motion (flexion or ex-

tension). Before the data collection began, the participants practiced the motion with the examiner. Five cycles of motion were recorded. With use of the cine-loop function, the image was reduced to 37% of real-time motion and recorded. This play speed maximized the recording frame rate and was the slowest limit that included an entire cycle of motion within the recording frame image (see Appendix).

Image Analysis

Analyze 7.0 software (Biomedical Imaging Resource, Mayo Clinic, Rochester, Minnesota) was used to review the recorded images, and the initial and final frames of the motion for each of the extension and flexion positions were chosen. On the basis of these images, the median nerve and the long-finger flexor digitorum superficialis tendon were outlined in both the extension and the flexion position. In order to quantify the shape of the median nerve (Fig. 2-A) and to document any shape changes, such as flattening, associated with tendon

Fig. 4

Distance between the median nerve and the long-finger flexor digitorum superficialis tendon. The flexion ulnar-radial distance with long-finger motion was significantly smaller than that with fist motion ($p < 0.01$). In addition, in the test of long-finger motion, the ulnar-radial distance in flexion was significantly smaller than it was in extension ($p < 0.01$). The flexion palmar-dorsal distance associated with long-finger motion was significantly larger than that associated with fist motion ($p < 0.01$). The I-bars indicate standard deviation, the top and bottom of each bar indicate the range, and the horizontal line within each bar indicates the mean.

motion, we measured the perimeter, cross-sectional area, aspect ratio of a minimum enclosing rectangle (Fig. 2-B), and circularity (Fig. 2-C) of the median nerve.

Displacement was defined as the distance of the centroid coordinates between the digital extension and flexion positions. In addition, the distance between the centroids of the median nerve and the long-finger flexor digitorum superficialis tendon was measured in both the ulnar-radial direction and the palmar-dorsal direction. The motions in the ulnar and radial directions were defined as positive and negative, respectively. The motions in the palmar and dorsal directions were defined as positive and negative, respectively.

To determine the minimum enclosing rectangle, the algorithm was started by fitting the smallest possible enclosing rectangle to the image and measuring the area of the rectangle. The image was then rotated in 1° steps over a range of 90° , and the rectangle area was recalculated at each step. The smallest rectangle found over the search range was defined as the minimum enclosing rectangle. The aspect ratio of the minimum enclosing rectangle was defined as the ratio of the minor axis length to the major axis length of the minimum enclosing rectangle (Fig. 2-B). We also measured the circularity—i.e., the ratio of the actual cross-sectional area to the area of a circle (the most compact shape) with the same perimeter—using the mathematical formula: $(\text{nerve perimeter})^2 / (\text{nerve area} \times 4\pi)$ (Fig. 2-C). Thus, a perfect circle would have a circularity of 1. In addition, the deformation ratio, which was defined as the value in the flexion position divided by the value in the extension position, was measured for each parameter. The average of the five data runs was calculated for each parameter and used for further analysis. All of the displacement and

deformation data were compared between the finger-flexion and finger-extension positions.

Statistical Analysis

Because these measurements had not been performed before, a detailed power estimate could not be created. Our sample size of fifteen was therefore created to provide an 80% power

TABLE I Median-Nerve Indices

	Mean (Standard Deviation)	
	Extension	Flexion
Area (mm^2)		
Fist motion	9.78 (1.35)	9.69 (1.45)
Long-finger motion	9.69 (1.47)	9.67 (1.55)
Perimeter (mm)		
Fist motion	14.30 (1.55)	14.50 (1.37)
Long-finger motion	14.22 (1.58)	15.35 (1.72)
Aspect ratio		
Fist motion	0.40 (0.10)	0.36 (0.07)
Long-finger motion	0.39 (0.09)	0.32 (0.05)
Circularity		
Fist motion	1.69 (0.30)	1.75 (0.28)
Long-finger motion	1.68 (0.28)	1.96 (0.29)
*P < 0.01.		

TABLE II Deformation Ratio

	Mean (Standard Deviation)		P Value
	Fist Motion	Long-Finger Motion	
Area	0.990 (0.049)	0.999 (0.061)	
Perimeter	1.016 (0.044)	1.080 (0.058)	<0.001
Aspect ratio	0.935 (0.164)	0.842 (0.163)	0.018
Circularity	1.046 (0.097)	1.172 (0.112)	<0.001

to detect a large difference (one standard deviation) at the 5% significance level.

The results were expressed as the mean and standard deviation. Since we collected the data from both hands from each subject, we used a mixed linear model to analyze the data. The comparisons between the fist and long-finger motions and between the extension and flexion positions were considered to be the fixed effect. Hands and persons were considered as random effects. P values of <0.05 were considered significant.

Source of Funding

The project was supported by National Institutes of Health/ National Institute of Arthritis and Musculoskeletal and Skin Diseases Grant AR49823, and was performed in our Clinical Research Unit, which is supported by National Institutes of Health Grant RR024150.

Results

There were no significant differences between the values for the right and left hands.

Displacement results are shown in Figure 3. The mean total displacement (and standard deviation) of the median

nerve was 2.09 ± 1.45 mm with fist motion and 2.07 ± 1.21 mm with long-finger motion; this difference was not significant. The mean total displacement of the long-finger flexor digitorum superficialis tendon with fist motion (1.80 ± 1.31 mm) was significantly larger than that with long-finger motion (1.17 ± 0.61 mm) ($p = 0.018$). The tendon moved in an ulnar and palmar direction with fist motion and in a radial and dorsal direction with long-finger motion. There was a significant difference in both ulnar-radial and palmar-dorsal displacement of the tendon between the fist and long-finger motions ($p < 0.01$).

The distances between the tendon and median nerve are shown in Figure 4. With finger extension, the ulnar-radial distances were 2.72 ± 2.13 and 2.45 ± 2.21 mm in the tests of fist and long-finger motion, respectively. With flexion, the ulnar-radial distances were 1.88 ± 3.53 mm and 0.08 ± 2.32 mm in the tests of fist and long-finger motion, respectively. The flexion ulnar-radial distance was significantly smaller with long-finger motion than it was with fist motion ($p < 0.01$). In addition, the analysis of long-finger motion showed the ulnar-radial distance to be significantly smaller in flexion than in extension ($p < 0.01$).

With finger extension, the palmar-dorsal distances were 2.12 ± 0.60 and 2.26 ± 0.53 mm in the tests of fist and long-finger motion, respectively. With flexion, the palmar-dorsal distances were 1.92 ± 0.85 and 2.56 ± 0.64 mm in the tests of fist and long-finger motion, respectively. The flexion palmar-dorsal distance with long-finger motion was significantly larger than that with fist motion ($p < 0.01$).

The deformation indices and ratios are shown in Tables I and II. The perimeter and circularity with long-finger motion were significantly increased compared with those values with fist motion ($p < 0.01$). The aspect ratio with long-finger motion was significantly decreased compared with that with fist motion ($p < 0.01$ for the index and $p = 0.018$ for the ratio).

Fig. 5
Illustration summarizing our findings.

Discussion

In this study, we demonstrated a significant difference in the transverse-plane motion patterns of the long-finger flexor digitorum superficialis tendon and the median nerve between fist and long-finger motions in fifteen normal human volunteers. In addition, the aspect ratio and the circularity of the median nerve in association with long-finger motion were decreased and increased, respectively, compared with those values with fist motion.

Before enrolling patients with carpal tunnel syndrome, we wanted to study in detail the normal motion characteristics. In future studies, we can now focus on the subset of movements and measurements that seem most relevant. We chose to evaluate fist motion because it is common to many hand activities. We chose to assess isolated long-finger motion for three reasons. First, the tendon is superficial and easy to acquire ultrasonographically. Second, it is adjacent to the median nerve and so might be expected to have more influence on nerve motion than a tendon that is more distant from the nerve. Third, a cadaver study showed a significant difference in the longitudinal median-nerve motion between simulated fist motion and isolated long-finger motion²⁴.

There have been several studies in which ultrasound was used to evaluate median-nerve motion^{1,22,23,25}. In a study of transverse motion of the median nerve under the flexor retinaculum in normal subjects, Nakamichi and Tachibana reported the mechanism of median-nerve motion as consisting of three steps². First, the increased tension in the flexor digitorum superficialis tendons of the index and long fingers caused a slight dorsoradial shift of the former and dorsal shift of the latter. Second, the median nerve displaced ulnarly into the newly opened space between the long-finger flexor digitorum superficialis tendon and the flexor retinaculum. Finally, the nerve and the two flexor tendons internally rotated together. Our observations showed similar motion patterns of the long-finger flexor digitorum superficialis tendon. In addition, we compared fist and single-digit motion, which are known to have different effects on the shear forces experienced by the subsynovial connective tissue²⁶. When the long-finger flexor digitorum superficialis tendon flexes independently, it moves toward the flexor retinaculum, but this motion is blocked somewhat by the median nerve so the tendon remains dorsal to the median nerve. In contrast, when the four fingers move together into a fist, the median nerve slips away from the flexor tendons and moves either ulnarly or radially, allowing the tendons to displace palmarly.

While Yamaguchi et al.²⁴ showed a significant difference in longitudinal displacement of the median nerve when comparing fist and long-finger motions, this difference was not found to be significant on cross-sectional ultrasound images in our study. We believe that this can be explained by the fact that we were studying motion in a plane perpendicular to the principal direction of tendon and nerve movement. In the longitudinal direction, the tendons move most because they are moving actively, while the nerve is moving passively, under indirect traction from the tendons as mediated by the sub-

synovial connective tissue. In the transverse plane, the magnitudes of motion are smaller and also less obviously related to the magnitude of longitudinal motion. Thus, while there were no significant differences in total displacement of the median nerve, there were significant differences in the distance between the median nerve and the tendon. These findings are summarized in Figure 5.

Although it has been suggested that there may be some deformation of the shape of the median nerve during finger motion², this has not been well characterized in normal subjects. In this study, we demonstrated that the aspect ratio decreased and circularity increased during isolated long-finger motion, most likely as a result of the compression of the nerve between the tendon and flexor retinaculum that occurs during isolated long-finger flexion. We believe that this is a potentially important observation. Normally, the median nerve and the flexor tendons are connected by the filmy, multilayered subsynovial connective tissue²⁷. In carpal tunnel syndrome, this connective tissue is thickened and relative motion of the structures within it is reduced^{28,29}. This fibrosis may therefore affect the ability of the median nerve to move out of the way of the tendons during finger motion, resulting in increased compression of the nerve with hand activities. Indeed, we believe that it is possible that fixation of the structures in the carpal tunnel by subsynovial connective-tissue fibrosis is the key feature in the etiology of carpal tunnel syndrome, as the fixation would prevent or reduce the dynamic rearrangement of the tendons and nerve with finger motion and thus predispose to local points of pressure concentration, as the structures become progressively unable to move away from each other during finger and wrist movements. As a result, rather than moving to the side, the nerve could become compressed between the tendon and the flexor retinaculum.

The ratio between the short and long diameters of the median nerve has been used to diagnose carpal tunnel syndrome^{15,16}. If the objects being measured are generally elliptical, the short-long diameter ratio and the aspect ratio would be identical. However, the development of high-resolution ultrasound had enabled us to show more structural details, and we observed variations in the shape of the median nerve, especially with finger flexion. Since the circularity and aspect ratio measurements allow more complicated shape descriptions, it may be advantageous to use these indices when evaluating the shape of the median nerve and its surrounding structures with ultrasonography.

The strength of our study is that we have described an *in vivo*, clinically applicable method with which to measure the displacement of tendons and nerves within the carpal tunnel with motion-direction-specific information, in addition to measuring the relationship between the nerve and tendon. Thus, the method introduced in this study may provide a way to assess the tendon-median nerve relationship when one or the other, or both, are abnormal, such as in carpal tunnel syndrome.

There are several limitations to our study. First, ultrasound measurements are known to be operator-dependent,

specifically with regard to transducer placement. However, in this study, the transducer was held in position with a custom fixture. Once the transducer was placed in position, the examiner focused only on the motion cycle on the screen, hopefully minimizing operator dependency. Second, we did not measure longitudinal motion in combination with transverse motion. The deformation that we described in this study is based on two-dimensional imaging. By combining these data with longitudinal imaging, it may be possible to understand displacement, deformation, and strain of the median nerve in three dimensions. Such data may also help investigators to derive mathematical models of the loading that such motions may confer on tendons, nerves, and subsynovial connective tissue and should be of great benefit in the assessment of the risk of connective-tissue or nerve injury associated with various hand movements. Third, as we captured images only over a few minutes, it is unclear if the translation or deformation of the nerve corrected or changed over time. Fourth, we made the ultrasound images at the proximal edge of the carpal tunnel and did not image the middle or distal part of the tunnel. While several other investigators have used ultrasound measurements of the median nerve in the proximal part of the carpal tunnel diagnostically^{16,18,30}, more distal images may also be useful, especially in patients with carpal tunnel syndrome, as these are more common sites at which to observe median nerve compression clinically. However, making images at the middle or distal part of the carpal tunnel requires the application of transducer pressure on the relatively thicker subcutaneous tissues of the palm. This pressure may affect the motion of the immediately subjacent median nerve and flexor tendons. For these reasons, we chose to limit our imaging to the proximal part of the carpal tunnel. In the future, we may study more distal images as well. Fifth, a single examiner reviewed the images in our study and we did not assess intra-examiner differences. Finally, we did not test patients with

carpal tunnel syndrome. We chose to limit the study to normal subjects so that we could investigate in detail the normal mechanics of the tendons and nerve with ultrasonography before trying to investigate the abnormal condition. Now that we have these normal values, we can compare our indices between large numbers of patients with carpal tunnel syndrome and normal subjects.

In conclusion, we have presented a method with which to assess cross-sectional displacement and deformation of the median nerve during various finger motions. The findings suggest that median nerve deformation may be affected more by single-digit motion than by fist motion. This methodology and these indices may be useful to investigate the mechanical function of the median nerve and the flexor tendons in patients with carpal tunnel syndrome.

Appendix

Videos demonstrating the dynamic ultrasound studies are available on our web site at jbjs.org (go to the article citation and click on "Supplementary Material"). ■

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