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Transverse Ultrasound Assessment of Median Nerve Deformation and Displacement in the Human Carpal Tunnel during Wrist Movements

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Abstract

The symptoms of carpal tunnel syndrome, a compression neuropathy of the median nerve at the wrist, are aggravated by wrist motion, but the effect of these motions on median nerve motion are unknown. In order to better understand the biomechanics of the abnormal nerve, it is first necessary to understand normal nerve movement. The purpose of this study was to evaluate the deformation and displacement of the normal median nerve at the proximal carpal tunnel level on transverse ultrasound images during different wrist movements, in order to have a baseline for comparison with abnormal movements. Dynamic ultrasound images were obtained in both wrists of 10 asymptomatic volunteers during wrist maximal flexion, extension and ulnar deviation. In order to simplify the analysis, the initial and final shape and position of the median nerve were measured and analyzed. The circularity of the median nerve was significantly increased and the aspect ratio and perimeter were significantly decreased in the final image compared to that in the first image during wrist flexion with finger extension, wrist flexion with finger flexion and wrist ulnar deviation with finger extension ($p<0.01$). There were significant differences in median nerve displacement vector between finger flexion, wrist flexion with finger extension and wrist ulnar deviation with finger extension (all $p<0.001$). The mean amplitudes of the median nerve motion in wrist flexion with finger extension (2.36±0.79 NU), wrist flexion with finger flexion (2.46±0.84 NU) and wrist ulnar deviation with finger extension (2.86±0.51 NU) were higher than those in finger flexion (0.82±0.33 NU), wrist extension with finger extension (0.77±0.46 NU) and wrist extension with finger flexion (0.81±0.58 NU) ($p<0.0001$). In the normal carpal tunnel, wrist flexion and ulnar deviation could induce significant transverse displacement and deformation of the median nerve.

Keywords

Ultrasound; Median Nerve; Carpal Tunnel Syndrome

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INTRODUCTION

Carpal tunnel syndrome (CTS) is the most common peripheral nerve entrapment syndrome, with a prevalence of 3.7% in the general US population (Papanicolaou, McCabe 2001). One plausible mechanism of CTS is median nerve impingement by one or more of the nine digital flexor tendons in the carpal tunnel. During finger or wrist movement, the median nerve stretches passively, under traction from finger motion, where the nerve attaches distally, as well as both longitudinally and transversely in response to the motion of the surrounding tendons, which move actively in the carpal tunnel. Longitudinal sliding of the median nerve in the carpal tunnel has been observed both in vitro (Szabo, Bay 1994, Coppieters and Alshami 2007, Wright, Glowczewskie 1996, Yamaguchi, Osamura 2008) and in vivo (Hough, Moore 2007, Tuzuner, Ozkaynak 2004). Wright et al. showed in a cadaver study that motion of the wrist and fingers could induce substantial excursion of the median nerve at the wrist. With wrist motion, the mean total median nerve excursion was 5.6 mm (4.3±1.95 mm in extension and 1.25±0.81 mm in flexion) (Wright, Glowczewskie 1996). Using motion techniques which aimed to let the median nerve slide through the carpal tunnel while minimizing the strain, longitudinal excursions of up to 12.4 mm were observed (Coppieters and Alshami 2007). In contrast, in patients with CTS the longitudinal gliding of the median nerve at the wrist is decreased compared to normal subjects (Hough, Moore 2007).

However, while these studies provide valuable information about the proximal-distal movement of median nerve in the carpal tunnel, the tunnel is a three dimensional structure. Studying the transverse plane movement of the median nerve in the carpal tunnel is also important, and has gained increasing attention in recent years. On transverse section, both radial-ulnar and palmar-dorsal movement of the median nerve occurs in response to wrist or even single digit motion (Erel, Dilley 2003, Nakamichi and Tachibana 1995, van Doesburg, Yoshii 2010, Yoshii, Villarraga 2009). As with longitudinal motion, the transverse movement of the median nerve in response to finger movement is reduced in patients with CTS compared to normal subjects (Erel, Dilley 2003).

In contrast to studies on the transverse movement of the median nerve associated with finger movement, only a few studies have addressed the transverse movement of the median nerve associated with wrist movement. The most common maneuver, however, to provoke the symptoms of CTS, the Phalen test, is wrist flexion without any finger motion (Tetro, Evanoff 1998). In addition, strong pinch or grip associated with wrist flexion is considered to be a risk factor for CTS (Feuerstein and Fitzgerald 1992, Harber, Bloswick 1993). Up to date, little is known about the kinematics of the median nerve during these movements.

Several studies have used MRI to measure the displacement or deformation of the median nerve at some specific wrist positions (Goetz, Baer 2012, Goetz, Thedens 2010, Greening, Smart 1999, Zeiss, Skie 1989). Yet MRI has limitations in demonstrating the dynamic movement of the median nerve during wrist movement. High-frequency ultrasound has become an important musculoskeletal imaging modality due to its portability, low cost, ease of use, comfort for the patient, high resolution, and capacity for dynamic imaging. While several ultrasound studies have been performed to observe the mobility of median nerve on transverse section, their data were obtained either semi-quantitatively or at specific wrists positions, as opposed to imaging the nerve dynamically as the wrist moved (Cartwright, White 2011, Greening, Lynn 2001).

In previous studies of nerve position in the carpal tunnel, static images were obtained at various wrist positions. Such studies do not allow the analysis of the dynamic effect of tendon motion or its impact on nerve motion. In this study, therefore, we analyzed dynamic ultrasound images in order to evaluate the deformation and displacement of the median nerve in vivo. We hypothesized that certain wrist motions might result in significant deformation and/or displacement of the median nerve in the carpal tunnel.

MATERIALS AND METHODS

This study protocol was approved by our institutional review board. Ten asymptomatic volunteers (four males and six females), with a mean age of 39.1± 9.8 years, were recruited. Individuals were excluded if they had the following conditions: body mass index (BMI) greater than 30, cervical radiculopathy, rheumatoid arthritis, osteoarthritis, degenerative joint disease in the hand or wrist, flexor tendinitis in the hand or wrist, gout, kidney failure on hemodialysis, sarcoidosis, peripheral nerve disease, amyloidosis, or fractures to the hand or wrist. Written informed consent was obtained from all participants.

Ultrasound Examination

Each subject was imaged while sitting with the shoulder in neutral position and the forearm supinated. The forearm of the subject was put on a custom-made table with the wrist in the neutral position. An ultrasound scanner (Acuson Sequoia C512, Siemens Medical Solutions, Malvern, PA) was used, equipped with a linear array transducer (name: 15L8; frequency: 8–14MHz). The depth of the ultrasound image was adjusted to 25 mm- 30 mm according the thickness of the examined hand. Ultrasound examinations were performed by a radiologist with more than 5 years' experience in musculoskeletal ultrasound. The image acquisition frame rate was set at 70Hz with minimal image compression. Both hands of each subject were imaged.

To study the transverse movement of the median nerve in the carpal tunnel, dynamic cross-sectional images of the carpal tunnel were obtained by placing the transducer at the proximal carpal tunnel. (Fig. 1) The proximal carpal tunnel was defined as the area between the pisiform and the scaphoid tubercle; these two landmarks are easily palpable in all hands. The transducer was maintained perpendicular to the median nerve in order to get clear images and to avoid anisotropic artifact. To keep the transducer stable during finger or wrist motion, a custom-made transducer-fixing device was fastened at the subjects' palm. For minimization of compression of the tissue in the carpal tunnel, the transducer was applied to the skin without additional pressure. To measure the wrist angle during wrist movement, a goniometer (CXT102, Crossbow) was fixed on the back of hand. The wrist angles were collected simultaneously with the ultrasound images.

Dynamic ultrasound images were obtained during the following finger and wrist movements:

1. Finger flexion, defined as the wrist held in the neutral position while all four fingers and the thumb moved from full finger extension to maximal flexion to make a fist;
2. Wrist flexion with finger extension, defined as wrist motion from the neutral position to maximal flexion while all fingers were held in full extension;
3. Wrist flexion with finger flexion, defined as wrist motion from the neutral position to maximal flexion while all fingers were flexed to form a fist;
4. Wrist extension with finger extension, defined as wrist motion from the neutral position to maximal extension while all fingers were held in full extension;
5. Wrist extension with finger flexion, defined as wrist motion from the neutral position to maximal extension while all fingers were flexed to form a fist;

6. Wrist ulnar deviation with finger extension, defined as wrist motion from the neutral position to maximal ulnar deviation while the fingers were held in full extension.

The subjects were asked to move in synchrony with a metronome, beating at 40 pulses per minute (0.67 Hz), thus requiring 1.5 s to complete the finger or wrist movements. Each movement was repeated 3 times, and the clip in which the median nerve was observed most clearly was chosen for final analysis. Before data collection, the participants practiced the assigned motion 2 to 3 times with the examiner.

Image Analysis

All images were evaluated using Analyze 11.0 software (Mayo Clinic, Rochester, MN). After the initial and final frames of the motion were selected and reviewed, the median nerve was outlined manually using a continuous boundary trace just within the echogenic boundary of the nerve (Duncan, Sullivan 1999). Area, perimeter, circularity and aspect ratio of a minimum-enclosing rectangle (MER) of the median nerve were calculated automatically. Circularity was defined as:

$$circularity = 4\pi \bullet \frac{area}{perimeter^2}$$

If the circularity is 1, the outlined polygon resembles a perfect circle; less than 1 indicates a deviation of a circle (e.g., oval or irregular shaped polygon). The minimum-enclosing rectangle was determined as the smallest possible enclosing rectangle to the median nerve. The aspect ratio was defined as the ratio of the major axis divided by the minor axis of this rectangle (Erel, Dilley 2003).

The position of the nerve was defined as the centroid coordinates of the median nerve in the first and final images of each motion sequence. The displacement in ulnar-radial (*x*) and palmar-dorsal directions (*y*) was calculated by comparing the initial and final centroid positions. The amplitude of median nerve displacement during each movement was calculated as $\sqrt{x^2+y^2}$. To analyze motion direction the palmar and ulnar directions were defined as positive and the radial and dorsal directions were defined as negative.

Normalization of Measurements

The measurements of area, perimeter, displacement of median nerve were normalized to hand length, defined as the distance from the tip of the middle finger to the midline of the distal wrist crease when the forearm and hand were supinated on a table (Clerke, Clerke 2005). Normalized results were presented as Normalized Units (NU) in which 1 NU= 1% of the normalized length. Thus, if the hand length was 100 mm and the actual measurement of interest (e.g., nerve motion) was 3 mm, the measurement would be expressed as 3 NU, i.e., 3% of the hand length. Area was also normalized by dividing by hand length, and so is also represented in NU. The mean hand length was 179.25 ± 10.20 mm. Thus, one normalized unit (NU) was roughly 1.8± 0.1 mm.

Reliability of Median Nerve Measurements

To assess intra-observer agreement, one examiner re-analyzed the ultrasound data for the dominant hand in each subject. The interval of the two analyses was at least 3 months. Area, perimeter, aspect ratio of MER, circularity on the first image and final image and the displacement amplitude of the median nerve were measured with the same Analyze 11.0 software.

To assess inter-observer agreement, two examiners analyzed the same ultrasound data for wrist flexion with finger extension of the dominant hand in each subject. Area, perimeter, aspect ratio of MER, circularity on the first image and final image and displacement amplitude of median nerve were measured with the same Analyze 11.0 software.

Data Analysis

Analysis JMP 9.0 (SAS Institute, Cary, North Carolina) was used for the paired t-test and t-test, custom Matlab programs were used for the bivariate statistics and SPSS version 12.0 (SPSS, Inc, Chicago, IL) was used for the intraclass correlation coefficients (ICC). All results are expressed as mean ± standard deviation. A paired t-test was used to analyze the difference of median nerve parameters between the dominant and non-dominant hands and t-test between the different wrist movements. The difference of the median nerve displacement vector between different movements was analyzed using the bivariate Mardia's two-sample test and the Mardia-Watson-Wheeler non-parametric test (Batschelet 1981). The mean vector (in polar coordinates) was used to represent the sample center. The standard ellipse, representative of sample variation, and Hotelling's confidence ellipse parameters ($\alpha = 0.05$) were calculated for each motion to describe sample variation. The p-values of less than 0.05 were considered statistically significant. Intra- and inter-observer agreements were examined using ICC and their 95% confidence intervals (Skou and Aalkjaer 2013).

RESULTS

The Maximal Wrist Angles with Different Wrist Movements

There was no significant difference in the maximal wrist angle between the dominant and non-dominant hands during any of the movements ($p>0.05$). Thus, we used the mean value of all 20 wrists to do the comparison between the different wrist movements. There was no difference in the maximal wrist angle between wrist flexion with finger extension and wrist flexion with finger flexion or between wrist extension with finger extension and wrist extension with finger flexion ($P>0.05$).

Measurements of Dominant versus Non-Dominant Hand

There was no difference in the area, perimeter, circularity aspect ratio or amplitude of displacement of the median nerve between the dominant and non-dominant hands for any movements ($p>0.05$). Thus, we used the mean value of all 20 wrists to do the comparison between the different wrist movements.

The Deformation of the Median Nerve during Finger and Wrist Movements

The area, perimeter, circularity and aspect ratio of median nerve for the first and final images of the various wrist movements are shown in Table 1. Significant differences between the first and last images were found for area, perimeter, circularity and aspect ratio of the median nerve during various movements. There was a significant difference found for the median nerve area solely for wrist flexion with finger extension. The circularity of the median nerve was significantly increased and the aspect ratio and perimeter were significantly decreased in the final image compared to that in the first image during wrist flexion with finger extension, wrist flexion with finger flexion and wrist ulnar deviation with finger extension ($p<0.01$) (Fig. 2–4). The circularity of the median nerve was significantly increased and the aspect ratio decreased in the final image compared to the first image during wrist extension with finger extension ($p<0.05$). There was no significant difference found for any of these parameters between the first and final images for finger flexion or wrist extension with finger flexion ($p>0.05$).

The Displacement Vector of the Median Nerve during Finger and Wrist Movements

Mean vectors and parameters for variation confidence limits - major and minor ellipse axes (a and b) and inclination (ψ) - for all motions are included in Table 2.

There was no significant difference in the motion vector of the median nerve between wrist flexion with finger extension and wrist flexion with finger flexion (p=0.067). There was a significant difference in the motion vector of the median nerve between wrist extension with finger extension and wrist extension with finger flexion (p=0.012), between finger flexion, wrist flexion with finger extension and wrist ulnar deviation with finger extension ($p <$ 0.001) (Fig. 5), and between finger flexion, wrist extension with finger extension and wrist extension with finger flexion (all $p <$0.05).

The Amplitude of Median Nerve Displacement during Finger and Wrist Movements

There was a significant difference in the amplitude of the median nerve motion among the movements (p<0.0001) (Fig. 6). The mean amplitudes of the median nerve motion in wrist flexion with finger extension (2.36±0.79 NU), wrist flexion with finger flexion (2.46±0.84 NU) and wrist ulnar deviation with finger extension (2.86±0.51 NU) were higher than those in finger flexion (0.82±0.33 NU), wrist extension with finger extension (0.77±0.46 NU) and wrist extension with finger flexion (0.81±0.58 NU). There was no difference in the amplitude of the median nerve between wrist flexion with finger extension, wrist flexion with finger flexion and wrist ulnar deviation with finger extension (p=0.1204) or between finger flexion, wrist extension with finger extension and wrist extension with finger flexion (p=0.9560).

Intra- and Inter-Observer Agreement of Median Nerve Measures

Intra- and inter-observer agreement for the area, perimeter, aspect ratio of MER, circularity and displacement of median nerve are summarized in Table 3. The intra-observer and inter-observer agreements were good to excellent for all measures, with the ICC ranging from 0.86 to 0.98.

DISCUSSION

Studying the transverse movement and shape of the median nerve in the carpal tunnel is important to understand the kinematics of the median nerve in both physiological and pathophysiological states. Ultrasound is a useful tool for such purposes, because it can obtain dynamic information about the deformation and displacement of the median nerve throughout the full range of wrist and finger motion.

Repetitive wrist movements are associated with CTS (Feuerstein and Fitzgerald 1992, Harber, Bloswick 1993). The motion of wrist flexion is also used as a provocative test to diagnose CTS. The most common test for CTS is the Phalen test in which the patient is asked to hold their wrists in complete and forced flexion (pushing the dorsal surfaces of both hands together) for 30–60 seconds. Characteristic symptoms such as burning, tingling or numb sensation over the thumb, index, middle and ring fingers indicates a positive test result and suggests carpal tunnel syndrome (Tetro, Evanoff 1998). Our results show that some wrist movements, such as maximal flexion and ulnar deviation, cause significant transverse displacement of the median nerve in the carpal tunnel. In addition, we have shown that the transverse motions are less affected by finger movement. This was as expected, since it is more logical that finger motions have a greater effect on longitudinal nerve motion than on transverse motion.

In this study, we quantitatively evaluated the deformation of the median nerve during different wrist movements. We found that the circularity of the median nerve was increased and the aspect ratio and perimeter were decreased during maximal wrist flexion and ulnar deviation. Other studies also found that the median nerve deforms during wrist movement, although their results were qualitative, depicting the shape of median nerve simply as flattened, oval or round (Greening, Smart 1999, Zeiss, Skie 1989). The significant deformability of the median nerve during wrist flexion and ulnar deviation in normal subjects may be related to its internal structure. Histologically, a peripheral nerve is composed of axons, which are bundled by 3 connective tissue layers; the endoneurium, the perineurium, and the epineurium. These connective tissues contain collagen fibrils, elastic fibers and endoneurial fluid (Gamble and Eames 1964). During extraneural compression induced by wrist movement, the median nerve could have transient and reversible deformation due to displacement of nerve fascicles in the nerve trunk. Although continuous compression would eventually cause endoneurial fluid displacement, as it would flow to the edges of a compressive cuff (Dyck, Lais 1990), this endoneurial fluid displacement is likely to occur during a relatively slow course, and is probably not related to the deformation of the median nerve that we observed in association with wrist movement. In contrast, longstanding compression might produce progressive fibrosis in the epineurial and perineurial connective tissues. This has been observed in experimental animals as well as autopsy retrieved human specimens with nerve compression. This fibrosis would result in a permanently decreased compliance of the median nerve (Clark, Barr 2003, Novak and Mackinnon 1998, O’Brien, Mackinnon 1987). We hypothesize that the deformation capability of median nerve may be impaired in patients with CTS. Further studies in patients with CTS are needed to validate this hypothesis.

The analysis of the vector and amplitude of median nerve displacement in this study showed that wrist flexion and wrist ulnar deviation cause significant displacement of the median nerve, as compared to finger flexion without wrist movement, or with wrist extension. This significant difference in displacement of the median nerve may be due to the influence of adjacent tissues, either pushing or pulling the median nerve into certain directions. During wrist flexion, the flexor tendons move palmarly within the carpal tunnel, as the flexor tendons change their pulling angle and glide directly against the flexor retinaculum (Keir and Wells 1999). As these tendons move palmarly towards the position of the nerve, the nerve can experience one of the following two phenomena: it can remain in situ, and likely be compressed by the palmarly advancing tendons, or it can move to the locations that the tendons have vacated to escape the compression. We observed the latter median nerve kinematics in the normal hands in this study. Similarly, as the wrist deviates ulnarly the tendons would tend to move to the ulnar side of the wrist, thereby pushing the nerve radially. It is well known that patients with carpal tunnel syndrome demonstrate fibrosis of the synovial tissue within the carpal tunnel (Ettema, Amadio 2004, Lluch 1992, Mackinnon 2002, Tuncali, Barutcu 2005, van Doesburg, Mink van der Molen 2012). In such cases, one might expect diminished motion, and resulting deformation of the nerve with finger and wrist movement. Indeed, this has been observed as well (van Doesburg, Yoshii 2010).

In addition to the amplitude of nerve motion being different based on different combinations of wrist and finger motion, we also identified motion patterns in which the direction of nerve motion changed, even if the amplitude did not, such as between finger flexion and finger extension with the wrist extended.

In addition to nerve motion as a result of direct physical contact with the tendons, the nerve may also move under the influence of fluid pressure shifts within the carpal tunnel. Pressures within the carpal tunnel can rise substantially during finger and wrist motion (Goss and Agee 2010, Luchetti, Schoenhuber 1998). However, other studies have shown that this pressure elevation is primarily due to contact pressure, and not fluid pressure (Ko and Brown 2007, Smith, Sonstegard 1977). A study using bulb pressure to evaluate the contact pressure on the median nerve showed that the pressure increased markedly as the wrist flexion angle and ulnar deviation angle increased (Keir, Wells 1997).

We believe that our normal data will be helpful to understand the pathomechanics in patients at risk for or suffering from early stages of CTS. The subsynovial connective tissue (SSCT), which fills the space between the tendons, and the space between the tendons and the median nerve, is normally filmy and supple, and thus could facilitates the smooth gliding of the median nerve between the flexor tendons and flexor retinaculum during finger and wrist movements. In patients with CTS, the SSCT becomes fibrotic and stiff, which could alter the gliding characteristics of the SSCT, and, thus of the nerve as well (Ettema, Amadio 2004, Ettema, An 2008, Ettema, Zhao 2007, Lluch 1992, Oh, Zhao 2006). We hypothesize that nerve and tendon motion patterns that are altered by SSCT fibrosis might be useful to identify CTS prodromes, and perhaps even as ‘biomarkers’ that might suggest treatments to restore or preserve nerve mobility before symptoms become so severe that surgery is needed, and we plan to investigate this possibility in future studies.

Our study has several shortcomings. First, our study has a small sample size. Yet the promising results of this study do indicate that evaluating the transverse plane movement of the median nerve during wrist motion could provide more information about the mobility and deformability of the median nerve, and may prove useful in the assessment of carpal tunnel syndrome. Second, in this initial study we only analyzed the initial and final images, but the advantage of ultrasound is that the entire movement can be captured and analyzed. However, such an analysis is far more complex than that needed to identify a simple vector from initial to final position, and so we have begun with this simpler analysis. Now that we have demonstrated that ultrasound can, indeed, capture useful images of the overall movement, we plan to return and reanalyze the entire movement path, for more insights. Finally, the median nerve kinematics was only characterized in normal subjects. However, we consider this a necessary first step before analyzing abnormal conditions. The data presented in the current study will be useful as a baseline for future studies in CTS patient populations.

In summary, our study quantitatively evaluated the transverse plane displacement and deformation of the median nerve under different finger and wrist movements in the healthy wrist. Maximal wrist flexion and ulnar deviation may be useful for evaluating the displacement and deformation of the median nerve, since these motions produced the largest displacements and deformations of the normal median nerve. Further studies of transverse plane ultrasound of the median nerve are necessary to assess its clinical value in patients with CTS.

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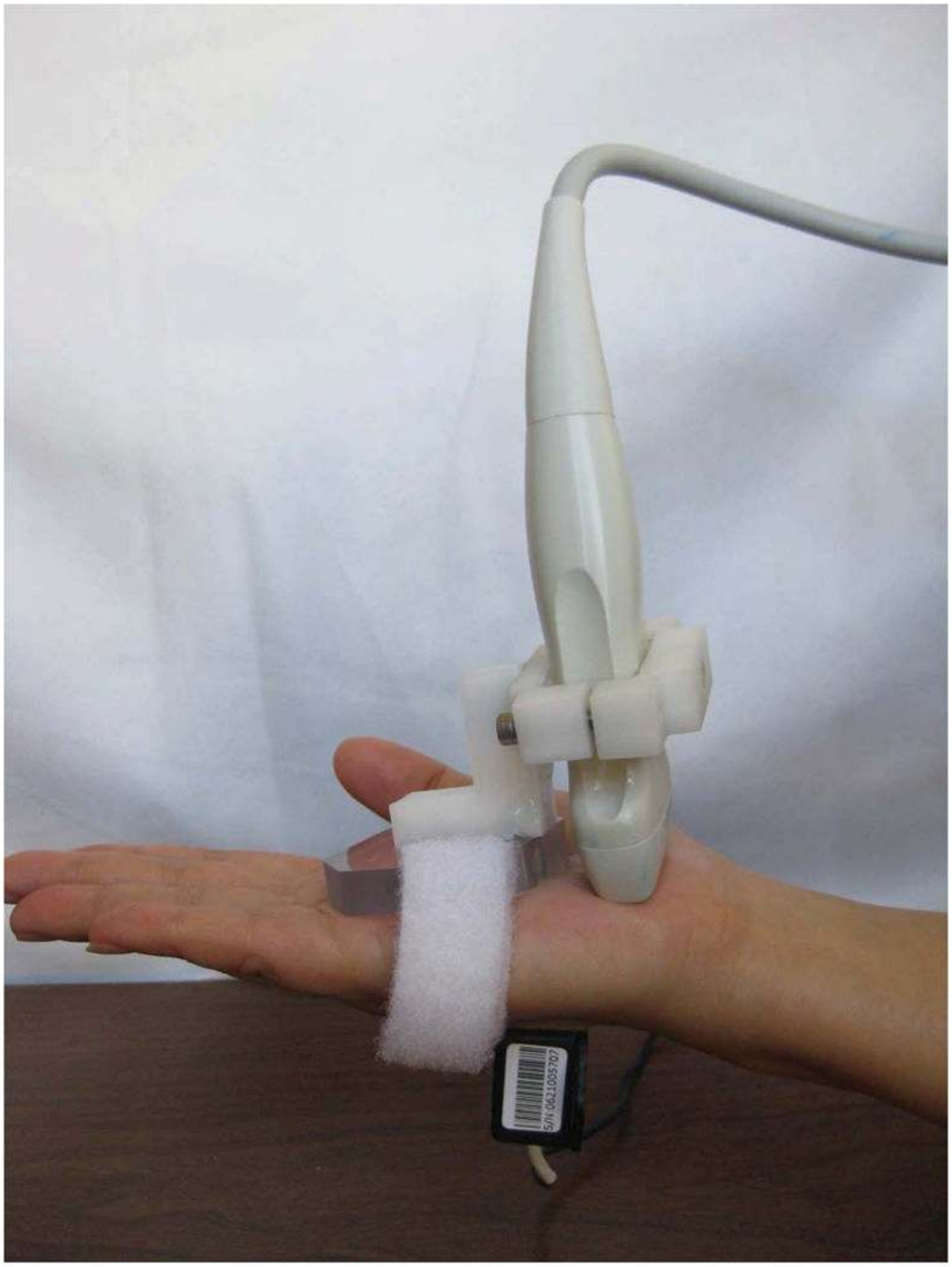

Figure 1.

Ultrasound examination setup. The transducer was placed at the proximal carpal tunnel. A custom-made transducer-fixing device was fastened at the subjects' palm to keep the transducer stable during finger or wrist motion. A goniometer was fixed on the back of hand to measure the wrist angle during wrist movement.

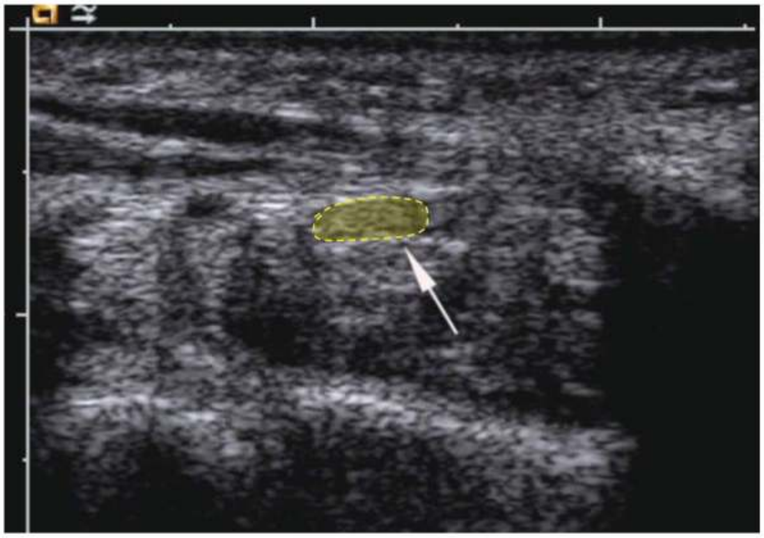

Figure 2.

The location of median nerve at the beginning of wrist flexion with finger extension: the median nerve (arrow) is located at the palmar midline position of the carpal tunnel.

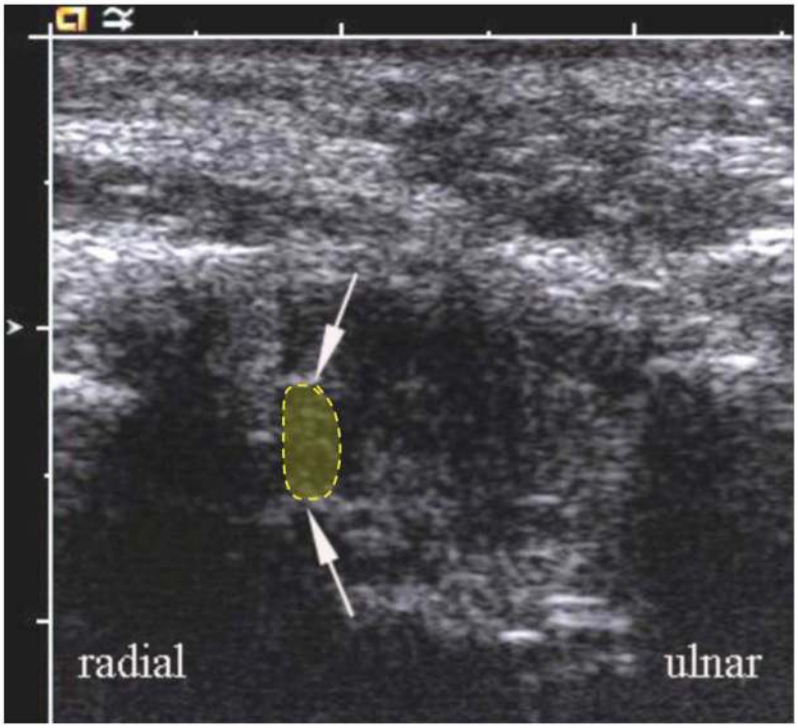

Figure 3.
The location of median nerve at the end of wrist flexion with finger extension: the median nerve (arrows) was located posteriorly in the carpal tunnel.

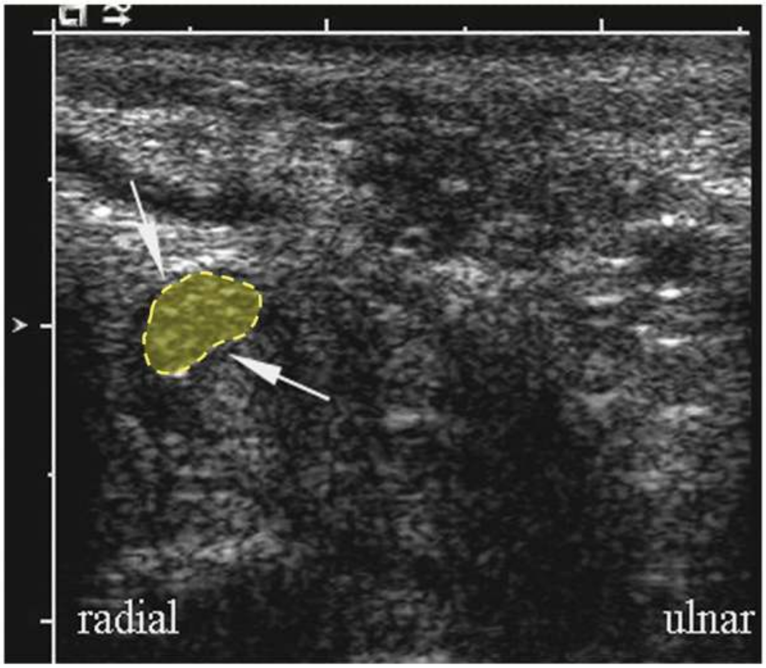

Figure 4.
The location of median nerve at the end of wrist ulnar deviation: the median nerve (arrows) was located between the flexor pollicis longus tendon and flexor retinaculum.

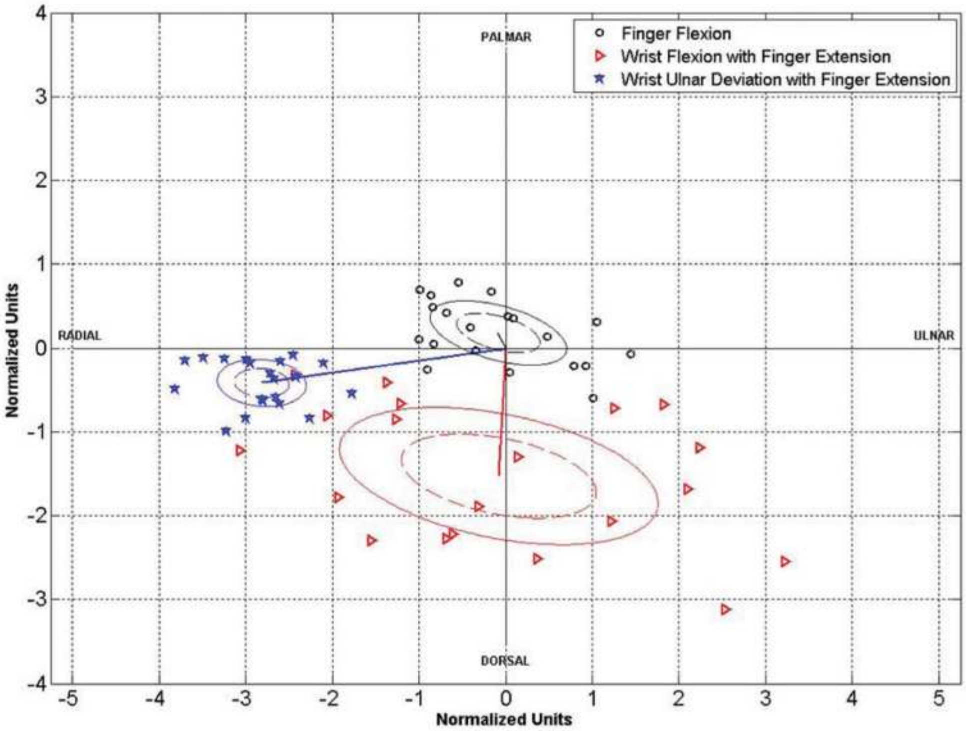

Figure 5.

Median nerve displacement vector for finger flexion, wrist flexion with finger extension and wrist ulnar deviation. (Solid ellipses represent standard deviation, dashed ellipses represent 95% confidence limits and the radial line represents the mean vector for each group.)

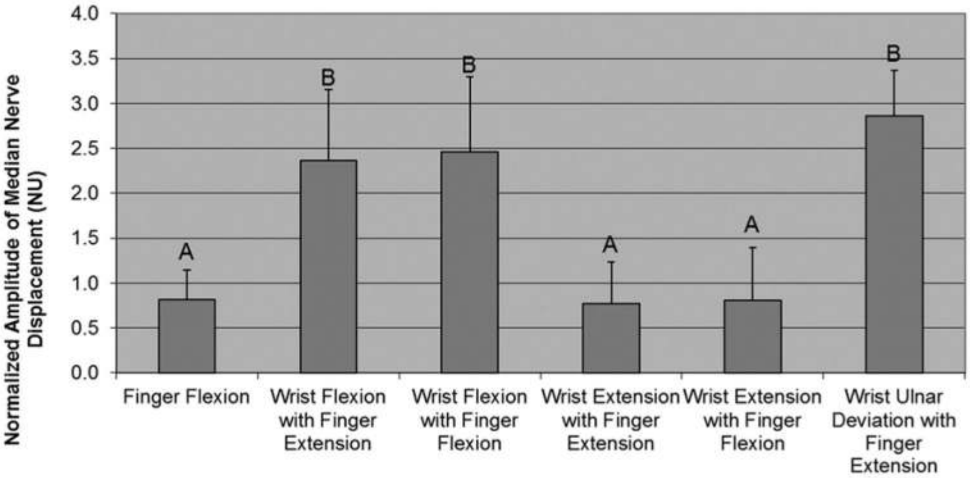

Figure 6.

The amplitude of median nerve displacement. The amplitude of median nerve motion in finger flexion, wrist extension with finger extension and wrist extension with finger flexion (A) were significantly less compared to wrist flexion with finger extension, wrist flexion with finger flexion and wrist ulnar deviation (B) ($p<0.0001$).

Table 1

The median nerve deformation parameters in different finger and wrist movements.

	Normalized Area (NU)	Normalized Perimeter (NU)	Aspect Ratio	Circularity
Finger Flexion				
First Image	5.27 ±0.73	8.51 ±1.02	3.11 ±0.68	0.52 ±0.10
Final Image	5.25 ±0.82	8.23 ±0.83	2.79 ±0.57	0.55 ±0.09
Wrist Flexion with Finger Extension				
First Image	4.74 ±0.92	7.97 ±1.51	2.78 ±0.54	0.55 ±0.13
Final Image	5.12 ±0.96(*)	6.91 ±0.80(**)	1.80 ±0.64(**)	0.76 ±0.08(**)
Wrist Flexion with Finger Flexion				
First Image	4.79 ±0.76	7.84 ±1.10	2.71 ±0.49	0.57 ±0.13
Final Image	4.55 ±0.61	6.27 ±0.52(**)	1.88 ±0.61(**)	0.81 ±0.05(**)
Wrist Extension with Finger Extension				
First Image	5.12 ±0.71	8.55 ±0.98	3.42 ±0.65	0.50 ±0.10
Final Image	5.49 ±1.03	8.32 ±1.07	2.88 ±0.46(**)	0.56 ±0.07(*)
Wrist Extension with Finger Flexion				
First Image	5.08 ±0.48	8.21 ±0.81	3.19 ±0.69	0.55 ±0.08
Final Image	5.10 ±0.81	8.08 ±0.93	2.91 ±0.73	0.55 ±0.07
Wrist Ulnar Deviation with Finger Extension				
First Image	5.20 ±0.63	8.31 ±0.97	2.73 ±0.52	0.54 ±0.10
Final Image	5.17 ±0.96	7.34 ±0.98(**)	1.82 ±0.55(**)	0.68 ±0.12(**)

[*] p <0.05,

[**] p<0.01 compared with the first image; NU: Normalized Units

Table 2

The mean vector and confidence limits for various parameters (α=0.05) of median nerve displacement during finger and wrist movements.

	Mean ρ (NU)[*]	**Mean θ**	**a (NU)[*]**	**b (NU)[*]**	**ψ**
Finger Flexion	0.2	117°	0.5	0.2	−16°
Wrist Flexion with Finger Extension	1.5	267°	1.2	0.5	−12°
Wrist Flexion with Finger Flexion	1.8	295°	1.1	0.5	−12°
Wrist Extension with Finger Extension	0.4	226°	0.5	0.2	−8°
Wrist Extension with Finger Flexion	0.5	182°	0.5	0.2	−3°
Wrist Ulnar Deviation with Finger Flexion	2.8	189°	0.3	0.2	−5°

[*] 1 NU = approximately 1.8 mm

Table 3

Intra- and inter-observer agreement of median nerve deformation and displacement in wrist maximal flexion with finger extension.

	Intra-observer Agreement ICC (CI 95%)	Inter-observer Agreement ICC (CI 95%)
First Image		
Area	0.96 (0.61, 0.99)	0.95 (0.67, 0.99)
Perimeter	0.94 (0.79, 0.98)	0.93 (0.71, 0.99)
Aspect Ratio	0.97 (0.84, 0.99)	0.96 (0.78, 0.99)
Circularity	0.86 (0.65, 0.97)	0.89 (0.60, 0.97)
Final Image		
Area	0.97 (0.87, 0.99)	0.97 (0.61, 0.99)
Perimeter	0.95 (0.78, 0.99)	0.91 (0.68, 0.98)
Aspect Ratio	0.98 (0.93, 0.99)	0.97 (0.86, 0.99)
Circularity	0.93 (0.72, 0.98)	0.89 (0.68, 0.97)
Amplitude of Median Nerve Displacement	0.91 (0.67, 0.98)	0.90 (0.60, 0.98)