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Speckle Tracking Ultrasound for Assessment of the Relative Motion of Flexor Tendon and Subsynovial Connective Tissue in the Human Carpal Tunnel

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Abstract

The objective of this study was to compare tissue Doppler imaging and speckle tracking ultrasound to assess the relative motion of flexor tendon and surrounding subsynovial connective tissue (SSCT).

Twenty normal human wrists were imaged with an ultrasound scanner. The two ultrasound methods measured the excursion and maximum velocity of the tendon and SSCT while subjects gripped three different sized acrylic tubes, and these were correlated with tendon excursions estimated from finger joint angle changes. The maximum velocity ratio ($=\text{SSCT}/\text{tendon velocity}$) and the shear index ($=[(\text{Tendon excursion}-\text{SSCT excursion})/\text{Tendon excursion}]\times 100\%$) were calculated.

The intraclass correlation coefficient was higher for joint angle/speckle tracking tendon excursion (0.642) than for joint angle/tissue Doppler excursion (0.377). The speckle tracking method could also discriminate differences in maximum velocity ratio and shear index for different tube sizes.

We conclude that speckle tracking may be useful in assessing the relative motion of tendon and SSCT.

Keywords

Carpal Tunnel; Subsynovial Connective Tissue (SSCT); Speckle Tracking; Velocity Vector Imaging (VVI); Shear Index; Relative Motion; Ultrasound

INTRODUCTION

Carpal tunnel syndrome (CTS), a pressure induced neuropathy of the median nerve at the wrist, is one of the most common clinical problems facing hand surgeons. Within the carpal tunnel, which is functionally a closed compartment (Cobb et al. 1995), there are flexor tendons, the median nerve, and a specially adapted paratenon, the subsynovial connective tissue (SSCT) (Guimberteau 2001; Ettema et al. 2004). The SSCT mediates movement between the flexor

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tendons and median nerve. As a framework for blood and lymph vessels, the SSCT plays a fundamental role in the nutrition of the structures embedded in it (Guimberteau 2001). Its mechanical significance relates to its effect on kinematics within the carpal tunnel (Guimberteau 2001). Previous studies have shown that SSCT motion characteristics (Ettema et al. 2008) and thickness (Ettema et al. 2006) are different in patients with carpal tunnel syndrome when compared to unaffected individuals. However, these observations have thus far required surgical exposure of the carpal tunnel and are not useful for the assessment of early changes in the SSCT in individuals affected by, or at risk for, CTS. A method that could assess SSCT function and anatomy in carpal tunnel would be helpful in strengthening the chain of evidence linking SSCT mechanics to CTS.

The use of diagnostic ultrasonography is attractive although other diagnostic studies are more commonly used in confirming the diagnosis of CTS and in excluding other pathologies (Buch-Jaeger and Foucher 1994; Bordalo-Rodrigues et al. 2004). The principal advantages of ultrasonography are its low cost, short study time, non-invasiveness, and the possibility of dynamic imaging. A pilot study has explored the ability of ultrasonography to visualize the SSCT in relation to the middle finger flexor digitorum superficialis (FDS) tendon, to qualitatively characterize local anatomy, and to analyze the SSCT thickness in vitro (Ettema et al. 2006). Another study quantitatively analyzed SSCT motion with tissue Doppler ultrasound by measuring its maximum flexion and extension velocity in relation to the middle finger FDS tendon velocity (Oh et al. 2007). Although tissue Doppler imaging could identify and track SSCT motion separately from that of its associated tendons, in these studies, both noted that the usefulness of Doppler imaging is limited by its angle dependence. This is particularly an issue for structures that move in three dimensions, such as the tendons in the carpal tunnel.

Speckle tracking is a new, angle independent, ultrasound method that calculates and displays regional movement from routine black and white echo images in terms of velocity and direction. We wished to test the hypothesis that an image analysis approach based on speckle tracking could evaluate the relative motion and the velocity of the flexor tendons and SSCT in routine grayscale ultrasonographic carpal tunnel images. Thus, the purpose of this study was to compare between tissue Doppler derived techniques and a new ultrasound method based on speckle tracking to assess the relative motion of the flexor tendon and surrounding subsynovial connective tissue (SSCT) in the carpal tunnel in normal human subjects.

METHODS

This study protocol was approved by our Institutional Review Board (IRB). Ten normal volunteers (six male, four female), with a mean age of 33.6 $\pm$ 6.5 years, were recruited. The participants were excluded if they reported a history of carpal tunnel syndrome, cervical radiculopathy, rheumatoid arthritis, osteoarthritis, degenerative joint disease, flexor tendinitis, gout, hemodialysis, obesity, sarcoidosis, peripheral nerve disease, amyloidosis, or traumatic injuries to the ipsilateral arm.

Participants were given a brief description of the purpose of the research and the testing procedures during the initial contact. Since the IRB waived written consent for this minimal risk study, verbal consent was obtained from all who participated in the study. After giving informed consent, the ultrasound measurements were performed. Each subject was imaged lying supine with the shoulder abducted to 45 degrees, with the elbow fully extended and the forearm supinated. The forearm of the examinee was fastened on a custom-made table with the wrist in the neutral position. An ultrasound scanner (Acuson Sequoia C512, Siemens Medical Solutions, Malvern, PA) equipped with a model 15L8 linear array transducer was set to a depth of 20mm with a 14MHz image acquisition frequency. Ultrasound evaluation was performed by an orthopedic surgeon trained in pertinent measurements of velocity vector

imaging (VVI, Siemens Medical Solutions USA, Inc., PA, USA), and tissue Doppler imaging by an experienced sonographic technician and a cardiologist with expertise in sonography.

Image Acquisition Procedure

A mark was made on the skin surface at three levels: the wrist flexion crease, the hook of the hamate and the distal edge of the transverse carpal ligament. The levels of the hook of hamate and the distal edge of the transverse carpal ligament were identified by palpation and confirmed by ultrasonographic imaging. The wrist crease level was chosen for imaging, since this location avoids undesirable physical contact of the flexing fingers with the transducer and allows better control of the angle between the ultrasound beam and the structures of interest.

The transducer was placed just proximal to the wrist flexion crease with a custom holder in order to maintain a fixed position. The middle finger FDS tendon was identified by cross-sectional and longitudinal ultrasonographic imaging as the patient voluntarily flexed and extended the middle finger while simultaneously holding the other fingers extended. This maneuver isolates the FDS, and blocks the motion of the middle finger flexor profundus (FDP) tendon. Since tendons are fibrillar in morphology, we were able to recognize the flexor tendon as a moving structure with a multitude of parallel striations. Then, the surrounding soft tissue and the immobile transverse carpal ligament were identified more palmarly.

To evaluate the discrimination sensitivity of our ultrasound methods, small, medium and large acrylic tubes, 3.8, 5.1, and 6.4 cm (1.5, 2.0 and 2.5 inch) in diameter, respectively, were used to limit tendon excursion. The participants were asked to flex and extend with four fingers (index, middle, ring, little) from full finger extension to the maximum flexion possible when gripping the various tubes. The participants were asked to move consistently and repeatedly, with a metronome marking a beat of 0.8 Hz for each direction (flexion or extension) of motion. Before data collection, the participants practiced the motion with the examiner. (Figure 1)

For the VVI method, the image acquisition frame rate was maintained at 70Hz, and the image compression was set to low. The image was recorded for three flexion-extension cycles for each tube size. Using 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 to include one full motion cycle in the recording frame. Three complete motion cycles were recorded for each subject for each tube.

The tissue Doppler method has been described previously (Ettema et al. 2006). In brief, the velocity signals were obtained placing a pulsed wave cursor (a Doppler sampling window 1 mm long) over the sampling area of interest during finger motion. The angle correction was optimized to a cosine of 60 degrees. After recording the tendon motion cycles, the cursor was moved on to the SSCT. After confirming that tendon velocity was relatively constant between runs and that the Doppler shifts of SSCT and tendon were similar for similar velocities, the Doppler velocity spectra corresponding to the tendon and SSCT were recorded to capture three complete motion cycles for each subject for each tube. Both of the image acquisition procedures were performed in both right and left wrists for each subject, giving a total of 20 wrists for analysis.

Data Analysis

For the speckle tracking measurement, the images were analyzed with Syngo VVI software (Siemens Medical Solutions USA, Inc., PA, USA)(Chen et al. 2007). After importing the images into the software, one cycle of motion was reviewed. Using the period selector mode, the timing bars were set to the beginning and end of one motion. By a point-click approach, three markers were placed on the FDS tendon tissue speckles, perpendicular to the tendon

motion direction, with a distance between the two furthest markers of approximately one millimeter. Based on a previous cadaver study (Ettema et al. 2006), the SSCT was defined as the highly echoic layer at the border of the tendon. Since the SSCT is normally thinner than one millimeter, the three markers were placed in following positions: one at the border between the tendon and the highly echogenic layer; one in the highly echogenic layer; and one at the outer border of the highly echogenic layer. This marker placement resembled the Doppler gate. Since this software tracks the area bounded by the applied markers, these markers were considered as capturing a representative segment of SSCT.

The analysis was performed using the software's generic curve mode. Better tracking was identified by a clear difference in the color which characterized the motion direction (Figure 2. Supplementary materials show examples of tracking each tissue). Based on this color differentiation, the best tracking point was selected for data analysis. The velocity and strain time series data were calculated by the software and were saved in Excel (Microsoft, Redmond, WA) format. The maximum velocity for both flexion and extension were measured. In addition, as described below, the tendon and SSCT excursions were calculated based on the area under the velocity/time series data. This image analyzing process took about 1 hour for each tube size.

For the tissue Doppler measurement, a detailed plot of target tissue velocity (or Doppler shift frequency) against time was displayed in spectral Doppler mode (Cigali et al. 1996; Hough et al. 2000). In this mode, Doppler velocity spectra of the three flexion and extension motions were analyzed for the motions of the tendon and corresponding SSCT. Doppler velocity spectra were interactively outlined, and by placing the caliper at the peak of the Doppler signal, the machine calculated the maximum velocity. The maximum velocities for flexion and extension were defined by the highest and the lowest points, respectively, of the Doppler spectra. In addition, since the Doppler signal represents the velocity-time series, the velocity time integral was defined as the excursion (Hough et al. 2000). This required measuring the area under the Doppler velocity curve using Image J Software (National Institute of Mental Health, MD, USA) for both tendon and SSCT excursion. (Figure 3)

The averages of maximum velocities and excursions for three cycles for both tendon and SSCT motions for each tube size were used for further analysis. The ratio of the SSCT maximum velocity relative to tendon maximum velocity was calculated as the maximum velocity ratio. In addition, a shear index, which was defined by the following equation (Yoshii et al. 2008), was calculated:

$$[(\text{Tendon excursion} - \text{SSCT excursion})/\text{Tendon excursion}] \times 100 (\%)$$

Tendon Excursion Estimation from Joint Angle Measurement

To estimate the ability of the ultrasound methods to accurately measure tendon excursion, the tendon excursions were calculated from the known relationship between FDS tendon excursion and joint rotation (An et al. 1983). With the participants holding the tubes used in the ultrasound examination, the angles of the proximal interphalangeal (PIP) and metacarpophalangeal (MP) joints were measured at the dorsal aspect of the joints with a protractor. The distal interphalangeal (DIP) joint motion was not measured, since the FDS does not act on the DIP joint. The ultrasound analyst was blinded to the angle measurement result. Based on the work of An et al. (An et al. 1983), we used 0.62 cm and 1.19 cm as the FDS moment arms for the PIP and MP joints, respectively, to calculate the tendon excursion. Thus, the equation for the tendon excursion was defined as:

$$[0.62 \times \text{PIP joint angle (in radians)} + 1.19 \times \text{MP joint angle (in radians)}] \text{ (cm)}$$

Statistical Analysis

The intraclass correlation coefficient, was used to evaluate the correlation of the tendon excursion measurement from each of the two ultrasonographic methods and the estimation derived from the measurement of the change in joint angle. For the error analysis, the excursion from the joint angle rotation was considered the gold standard, and the difference of tendon excursion between each ultrasonographic method and the excursion from joint angle rotation were measured. A two-way analysis of variance (ANOVA), followed by Scheffe's post hoc test, was used to compare the differences in shear index and maximum velocity ratio for different tube sizes within the same measurement method. For the maximum velocity ratio, the differences in same direction motion (flexion or extension) were compared. The results were expressed as mean $\pm$ standard deviation (SD). P-values of less than 0.05 were considered statistically significant. All analyses were performed by SAS/STAT version 9.1.3 software (SAS institute Inc., Cary, NC).

RESULTS

Summary results of the relationship between the excursions from the ultrasound measurements and the excursions from the joint angle calculations are shown in Figure 4. The excursions from the speckle tracking measurements were underestimated when compared to the corresponding excursions calculated from the joint angles. There was also a trend to overestimate the excursions from the tissue Doppler derived measurement compared to the excursions derived from the joint angle calculations. The intraclass correlation coefficient between the excursions from the joint angle calculations and the speckle tracking measurements was 0.642. The intraclass correlation coefficient between the excursions from the joint angle calculations and the tissue Doppler measurements was 0.377. The mean difference between the excursions from the joint angle calculations and the speckle tracking measurements was 1.07 ± 0.27 cm. The mean difference between the excursions from the joint angle calculations and the tissue Doppler measurements was 0.44 ± 0.59 cm.

Summary results for maximum velocity ratio are shown in Figure 5. For the speckle tracking measurements, the maximum velocity ratio was smaller for the small size tube and larger for the large size tube, with a significant difference in the maximum velocity ratio between the small size tube and large size tube in the extension direction of motion ($P < 0.01$). There were also significant differences between small tube and large tube ($P < 0.01$), and between medium tube and large tube ($P < 0.05$) in the flexion direction. For the tissue Doppler measurements, there was no significant difference in the maximum velocity ratio between tube sizes in either direction of motion.

Summary results for shear index are shown in Figure 6. For the speckle tracking measurements, the shear indices were 39.4% ($\pm 13.3\%$), 31.3% ($\pm 9.9\%$), and 22.3% ($\pm 9.4\%$) for the small, medium and large size tubes, respectively. There were significant differences in shear index between each tube size for the speckle tracking method ($P < 0.01$). For the tissue Doppler measurement, the shear indices were 9.8% ($\pm 12.8\%$), 13.1% ($\pm 14.2\%$), and 2.1% ($\pm 14.6\%$) for the small, medium and large size tubes, respectively. There was no significant difference in the shear index between tube sizes for the tissue Doppler measurements.

DISCUSSION

This was a preliminary study using speckle tracking ultrasound to estimate the relative motion of structures in the human carpal tunnel. We demonstrated that an ultrasound method based on speckle tracking had the potential to evaluate tendon and SSCT motion. In addition, we found that the maximum velocity ratio and shear index were distinguishable for speckle tracking ultrasound. Although other methods have been used to measure tendon motion, such as fluoroscopy or direct intraoperative inspection, ultrasound is the most common and inexpensive method, and it is also non-invasive.

In recent years, tissue Doppler strain and strain rate imaging have been used generally to quantify tissue function. However, as a one dimensional method, tissue Doppler can only quantify the axial component of motion in an angle dependent manner. Once the angle between the ultrasonic beam and the tissue is beyond a certain range, the Doppler measurement loses its validity (Castro et al. 2000; Steinman et al. 2001; Galderisi et al. 2006).

Speckle tracking is based on two dimensional gray scale images and thus is angle independent in principle. The general principle of this technique relies on the tracking of acoustic signals (speckles) in the tissues from frame to frame throughout the motion cycle with an optimized pattern-matching algorithm. Because the speckles consist of a certain number of two-dimensional pixels, the tracking has good stability from one frame to the next. By reconstructing the deformation and motion of the speckles, the motion of fluid and tissue can be analyzed (Chen, et al. 2007). Speckle tracking is a mature method for echocardiographic analysis (Pirat et al. 2006; Chen et al. 2007; Zhang et al. 2008). The accuracy of speckle tracking and its clinical utility for the assessment of cardiac function has been demonstrated in several studies (Helle-Valle et al. 2005; Notomi et al. 2005).

In this study, we wished to analyze the motions of flexor tendons and their surrounding tissue using speckle tracking. Our goal was to measure simultaneously the motion of two separate structures, the tendon and SSCT, within the same cycle of motion and from the same acquired image, something that is not technically possible with the Doppler method. Because the speckle tracking software was originally developed for the evaluation of cardiac function, though, it was a challenge to use it for tendon motion analysis. However, by recording the reduced play speed image for one cycle of tendon motion, the speckle tracking method appropriately estimated tendon motion, and, indeed, did so with better correlation to an independent estimation of tendon excursion than tissue Doppler.

The difference between the excursions from the joint angle calculations and the speckle tracking measurements was larger than between the excursions from the joint angle calculations and the tissue Doppler measurements. However, the correlation coefficient of the excursion between the excursions from the joint angle calculations and the speckle tracking measurements was better than between the excursions from the joint angle calculations and the tissue Doppler measurements. This suggests that the speckle tracking was superior to detect the magnitude of the tendon excursion, but not as precise to measure excursion.

The maximum velocity ratio and shear index represent different aspects of tendon motion. While the maximum velocity ratio represents a specific instant in the motion cycle, the shear index summarizes the whole cycle of motion. The maximum velocity ratio in the speckle tracking method was lower for the small tube and higher for the large tube. Given a fixed cycle time, since the tendons needed to move a larger distance to grip the small tube it is logical that tendon velocity should be greater for the small tube than for the large tube. However, a previous cadaver study has shown that higher overall velocities are associated with lower maximum velocity ratios for tendon and SSCT (Oh et al. 2007). Our findings are consistent with this report.

The shear index represents the SSCT displacement relative to flexor tendon displacement. Any delay in the initiation of SSCT motion or decrease in SSCT velocity will lead to an increase in the shear index. In this study, motion around the small tube was associated with a higher shear index. This can be explained by a longer tendon excursion relative to SSCT excursion, producing a larger absolute difference between tendon and SSCT excursion. In a previous study, this shear index was investigated with a fluoroscopic assessment of the relative motion of FDS tendon and SSCT (Yoshii et al. 2008). That study showed that the shear index consistently increased until 70% of full tendon motion was achieved. In this study, excursion with the small size tube produced less than 70% of full tendon excursion, as derived from the joint angle measurements. Thus, the difference we observed in shear index for different tube sizes is consistent with data on shear index obtained from other methods.

Although ultrasound has been used to diagnose CTS, based on differences in static images of nerve morphology (Wong et al. 2002; Ziswiler et al. 2005; Klauser et al. 2009), less use has been made of its potential value in dynamically assessing tendon mechanics, and pathomechanics, within the carpal tunnel. By identifying movements in which the difference between tendon and SSCT motion is greatest, the speckle tracking method used in this study may provide a way to assess the presence or risk of SSCT shear injury within the carpal tunnel, and lead to a better understanding of the role of SSCT shear in CTS pathogenesis. In the future, by comparing the shear index and maximum velocity ratios between normal subjects and CTS patients, it may be possible to establish a new, non-invasive, inexpensive, and quantitative method to aid in the diagnosis of an early stage of CTS, or even a predisposition for CTS, in which the SSCT is structurally abnormal but the nerve is not. We are currently planning to test this method in patients with established CTS, in addition to recruiting more normal subjects to refine the methods described above.

There are several limitations in our study. First, we did not directly measure tendon excursion in vivo. We did find that there was an underestimation of tendon excursion with the speckle tracking method and an overestimation with the tissue Doppler imaging method compared to the implied excursion derived from joint angle measurements. The underestimation for the speckle tracking method may be due to slight differences in the alignment of the direction of tendon motion and the transducer. If there is a mismatch between the direction of tendon motion and the transducer, the tendon becomes faint on the monitor. In addition, in subjects with thick subcutaneous tissues, the image will also become faint. In such cases, the tracking may momentarily fail, resulting in an underestimation of the tendon excursion. For the Doppler method, the velocity is defined by the Doppler shift and the cosine of the angle between the ultrasound beam and the direction of the tendon motion. Thus, if the tendon motion angle to the ultrasound beam is smaller than the estimated angle correction, the Doppler shift will appear to be greater than it actually is, and the tendon velocity will be overestimated. These factors should be taken into consideration in future studies. Second, although the motions of flexor tendon and SSCT are three-dimensional, speckle tracking can only offer the two-dimensional information in one scan. However, the alternative, tissue Doppler, can only assess one dimension. Third, we did not adjust the moment arms based on the actual measurements of the specific hands in our study, but instead used mean values from a previous study (An et al. 1983). However, we believe that it is unlikely that the mean moment arm in our subjects would have varied significantly from the mean values reported previously. An et al. have shown that these moment arms are closely correlated with tendon excursion in normal hands. Moreover, to measure tendon excursion directly, we would have needed to surgically expose the tendons, which is ethically contraindicated in these normal subjects. A fourth limitation is that the results are operator dependent, specifically with regard to transducer placement. Again, however, this is more so for tissue Doppler imaging, which is highly dependent also on the angle of the cursor to the spectral steer of the cursor relative to the moving structure. For this reason, it may take longer to acquire appropriate images for the analysis than with a static ultrasonogram. In this

study, the transducer was held in position with a custom fixture. Once the transducer was placed in position, the examiner only focused on the cycle of the motion on the screen. This may help to minimize operator dependency. Fifth, while the differences in correlation coefficient favored speckle tracking, the correlations were only moderate. However, it is important to note that speckle tracking is an evolving technology, while tissue Doppler is a mature technology. Thus, we believe that the “upside” is greater for speckle tracking than it is for tissue Doppler. Finally, because this study was a pilot in vivo study, the number of participants was small and we did not assess inter-examiner or intra-examiner differences. These remain for future investigations. However, we found there is a potential to estimate the shear between the tissues with speckle tracking ultrasound. This seems to be a unique aspect of ultrasound imaging, which is impossible with other clinical imaging methods. We hope to modify this method for clinical use.

CONCLUSION

In conclusion, speckle tracking appears to be a potentially useful method to evaluate the relative motion of flexor tendon and SSCT in the carpal tunnel. In addition, we found that the maximum velocity ratio and shear index were distinguishable by this method. These may be useful indices to evaluate the pathomechanics of flexor tendons and SSCT in the carpal tunnel. We believe that further studies of this method would be worthwhile, both to refine the methods, and to compare images in subjects with and without carpal tunnel syndrome.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Figure 1.
Picture of the ultrasound exam set up 1) transducer, 2) acrylic tube, 3) transducer holder, 4) adjustable arm.

Figure 2.

An example of the speckle tracking measurement (tendon) 1) tracking markers, 2) trace of the tendon motion, 3) velocity wave form, 4) color differentiation for the different directions of motion.

Figure 3.

An example of the tissue Doppler imaging measurement (flexor tendon) 1) pulsed wave cursor, line shows angle correction, 2) the maximum velocity for flexion, 3) the area under the dotted line was measured for the excursion.

Figure 4.

The relationship between the excursion derived from change in joint angle and the ultrasound measurements A) tendon excursions from joint angle and speckle tracking method, B) tendon excursions from joint angle and tissue Doppler imaging method.

Figure 5. Maximum velocity ratio a) speckle tracking method, b) tissue Doppler imaging method. Pairs of values that are statistically different from each other are denoted (*), (**), (+) (*, +: $P < 0.01$, **: $P < 0.05$).

Figure 6. Shear Index. Pairs of values that are statistically different from each other are denoted (*), (**), (+) ($P < 0.01$).