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Speckle-Tracking Sonographic Assessment of Longitudinal Motion of the Flexor Tendon and Subsynovial Tissue in Carpal Tunnel Syndrome

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Abstract

Objectives—The aim of this study was to image both tendon and subsynovial connective tissue movement in patients with carpal tunnel syndrome and healthy control volunteers, using sonography with speckle tracking. To estimate accuracy of this tracking method, we used in vivo measurements during surgery to validate the motion estimated with sonography.

Methods—We recruited 22 healthy volunteers and 18 patients with carpal tunnel syndrome. Longitudinal sonograms of the middle finger flexor digitorum superficialis tendon and subsynovial connective tissue were obtained during finger flexion and extension. The images were analyzed with a speckle-tracking algorithm. The ratio of the sub-synovial connective tissue velocity to tendon velocity was calculated as the maximum velocity ratio, and the shear index, the ratio of tendon to subsynovial connective tissue motion, was calculated. For validation, we recorded flexor digitorum superficialis tendon motion during open carpal tunnel release.

Results—The shear index was higher in patients than controls ($P < .05$), whereas the maximum velocity ratio in extension was lower in patients than controls ($P < .05$). We found good intraclass correlation coefficients (>0.08) for shear index and maximum velocity ratio measurements between speckle-tracking and in vivo measurements. Bland-Altman analyses showed that all measurements remained within the limits of agreement.

Conclusions—Speckle tracking is a potentially useful method to assess the biomechanics within the carpal tunnel and to distinguish between healthy individuals and patients with carpal tunnel syndrome. This method, however, needs to be further developed for clinical use, with the shear index and maximum velocity ratio as possible differentiating parameters between patients with carpal tunnel syndrome and healthy individuals.

Keywords

carpal tunnel; motion; sonography; speckle tracking

Carpal tunnel syndrome is a compression neuropathy of the median nerve at the wrist level, of which the exact etiology remains unknown. The most commonly reported pathologic

finding is fibrosis of the subsynovial connective tissue, the lining around the tendons within the carpal tunnel.^{1,2} Ettema et al^{3,4} and Osamura et al⁵ showed that the mechanical properties of the subsynovial connective tissue and the motion mechanics in the carpal tunnel are altered in patients with carpal tunnel syndrome and suggested that this condition may be a consequence of the fibrotic changes of the subsynovial connective tissue, causing the synovium to be more tightly tethered to the tendon in patients than in healthy people. This alteration in subsynovial connective tissue mechanics could predispose to a vicious cycle of shearing injury to the subsynovial connective tissue.^{6,7}

The diagnosis of carpal tunnel syndrome is mostly clinical and is usually confirmed with nerve conduction studies. The use of sonography as a new method for diagnosing carpal tunnel syndrome has been extensively studied previously. However, most research has focused on the use of static cross-sectional imaging of the carpal tunnel, including parameters such as the cross-sectional area and shape of the median nerve, and bowing of the flexor retinaculum.^{8–12}

Assessment of the longitudinal motion of the median nerve and tendons within the carpal tunnel during finger motion has been studied as well, using tissue Doppler imaging.¹³ Tissue Doppler imaging has one big disadvantage, which is its angle dependency. Recently, a study showed that speckle tracking may be a useful method to evaluate the motions of the tendons and subsynovial connective tissue in the carpal tunnel, showing a better correlation with joint angle measurements than Doppler measurements did.¹⁴ Speckle tracking is a relatively new method, in which speckles in the sonogram are tracked from frame to frame, independent of the angle. This method has been used before to measure median nerve excursion in carpal tunnel syndrome.¹⁵ Yoshii et al¹⁴ were the first to assess the subsynovial connective tissue using sonography, and because of the possible mechanical change in motion of both the tendons and the subsynovial connective tissue in patients with carpal tunnel syndrome, it may be clinically relevant to be able to distinguish both.

The aim of this study was to image both tendons and subsynovial connective tissue movement in patients with carpal tunnel syndrome and compare their results with healthy control volunteers, using speckle tracking. This noninvasive evaluation of the tendon and subsynovial connective tissue motion may be useful to better understand biomechanics within the carpal tunnel and could be a potential diagnostic tool for carpal tunnel syndrome in the future. To estimate the ability of this speckle-tracking method to accurately measure tendon and subsynovial connective tissue excursion, we used direct measurements in the carpal tunnel during surgery to validate the motions estimated from sonographic measurements.

Materials and Methods

Sonographic Measurements

After getting approval from our Institutional Review Board, we recruited 22 healthy volunteers (12 men and 10 women; mean age, 35.1 years; range, 27–67 years) and 18 patients (5 men and 13 women; mean age, 52.1 years; range, 34–70 years) with idiopathic carpal tunnel syndrome diagnosed by clinical symptoms and electromyography. This population was a sample of convenience; we did not attempt to match age and sex in patients and controls. Patients were excluded if they had a history of any condition predisposing to carpal tunnel syndrome, such as arthritis, diabetes mellitus, or trauma to the lower arm. After receiving written consent from the participants, longitudinal sonograms of the middle finger flexor digitorum superficialis tendon and the subsynovial connective tissue were obtained by applying the transducer longitudinally from the hook of the hamate level (mid tunnel) to the wrist crease level (proximal tunnel). We used a 15L8 linear array

transducer and an Acuson Sequoia C512 ultrasound machine (Siemens Medical Solutions, Malvern, PA) set to a 15-MHz acquisition frequency. The depth was set to 20 mm, and the focus was adjusted to the level of the tendon. The frame rate was set to 30 Hz. Proper transducer positioning was ensured by identifying specific anatomic structures and detecting the flexor digitorum superficialis III tendon while flexing and extending the middle finger. Then, more palmarly, the surrounding soft tissue and the flexor retinaculum were identified as nonmoving structures. Tendons are easily recognizable because of their echogenic fibrillar structure consisting of parallel lines. The median nerve was recognized as a structure with multiple hypoechoic areas. In all healthy volunteers, measurements were taken bilaterally. In patients, measurements were taken from the affected arm(s). Participants were asked to flex and extend all fingers (index, middle, ring, and little) simultaneously while holding a 1.5-in-diameter cylinder at a pace of 0.8 Hz for each direction of motion. Before data collection, the participants practiced the motion with the examiner. Three motion cycles were recorded using the cine loop function, reducing the speed to 37% of real-time motion to maximize the recording frame rate.

The images were analyzed with Syngo VVI software (Siemens Medical Solutions). After uploading the images in the software, the period selector mode was used to set the timing bars to the beginning and end of one motion. Three markers were placed on the flexor digitorum superficialis tendon tissue speckles, with a distance between the two farthest markers of approximately 1 mm. The markers were placed perpendicular to the tendon motion direction, in the area between the distal radius and the carpal bones, which were typically seen on the sonogram. The subsynovial connective tissue was defined as the thin echogenic layer at the border of the tendon. Again, the three markers were placed, this time one at each border of the echogenic layer and one in between (Figure 1). Then the software's generic curve mode was selected to perform the analysis, providing the velocity and strain time series data. We then measured the maximum velocity for both flexion and extension positions and calculated the excursion of both the tendon and the subsynovial connective tissue based on the area under the velocity/time series data.

The analysis of the first cycle was used as a preconditioning analysis. The averaged maximum velocities and excursion for the second and third cycles of both the tendon and subsynovial connective tissue were used for further analysis. Two ratios were created, the first being the maximum velocity ratio, defined as the maximum velocity of the subsynovial connective tissue relative to the maximum velocity of the tendon, and the second being the shear index, calculated by the following equation: $[(\text{tendon excursion} - \text{subsynovial connective tissue excursion}) / \text{tendon excursion}] \times 100 (\%)$. This index is an indication of the shearing motion between the two structures.

Validation Measurements

The second part of our study was the in vivo validation of this method, using intraoperative videos of tendon and sub-synovial connective tissue motion during flexion and extension. A study with a similar intraoperative setup was done by Ettema et al.,⁴ who validated this method and reported an intraclass correlation coefficient of 0.88. On the basis of their study, we calculated that with a sample size of 6, we would have 80% power to detect a difference of 1.92 mm, which we consider to be potentially clinically important.

Four patients of the group studied with sonography underwent open carpal tunnel release, 2 of whom had bilateral release and the other 2 unilateral release. After getting written consent, we obtained the intraoperative videos as follows: Surgery was performed under local anesthesia without sedation because that would have affected cooperation of the patient. An open surgical incision extending from 1 cm proximal to the wrist crease to the mid palm was made. First the flexor retinaculum was transected, and then the carpal tunnel

was exposed by a self-retaining Weitlander retractor. A small window of approximately 3 mm in diameter was made in the visceral synovium and subsynovial connective tissue to expose the middle finger flexor digitorum superficialis tendon. With the wrist in the neutral position and the fingers passively extended to 0°, a mark was made on the middle finger flexor digitorum superficialis tendon surface with a surgical marker. Then the visceral synovium surface was marked at a level 15 mm proximal to the tendon mark. A third mark was made on the cut edge of the flexor retinaculum to serve as a reference point (Figure 2). The patient was asked to flex and extend the 4 fingers (index, middle, ring, and little) holding a 1.5-in-diameter cylinder, while a video camera (StrykeCam In-Light surgical camera; Stryker Communications, Flower Mound, TX) recorded the motion. A millimeter ruler was included in the camera field so that the data measured with the camera could be converted into a distance figure. The camera was set perpendicular to the operating table and the wrist, centering the tendons in the middle of the camera field. To avoid measurement errors, we did not zoom with the camera. After the motion was recorded, the operation proceeded as normally.

The intraoperative data were digitized to determine the motion characteristics of the 3 marks using Analyze 8.1 Software (Biomedical Imaging Resource, Mayo Clinic). All x and y coordinate data were converted from pixels to millimeters using the scale factor conversion obtained from the imaged ruler. The coordinates for the tendon and sub-synovial connective tissue were normalized relative to the fixed reference point to correct for any translational motion of the image during data collection. Proximal and distal motions were defined as positive and negative motions, respectively. The coordinates at the initial positions for each marker were defined as zero excursion. For the tendon and subsynovial connective tissue, the distances along the motion direction of the tendon excursion were calculated. On the basis of these data, we calculated the shear index using the formula noted above.

Data Analysis

A repeated measures model was used to compare the differences in the shear index and maximum velocity ratio between the patients with carpal tunnel syndrome and healthy controls. Controls and patients, as well as left and right hands, were fixed effects. For the maximum velocity ratio, the differences in same-direction motion (flexion or extension) were compared. For the sonographic measurements, we recorded 3 motion cycles of each hand in every patient. The first recording was used as preconditioning, whereas the last two were used for analysis and for intra-rater reliability calculation.

The interclass correlation test was used to evaluate the correlation between the tendon excursion from the speckle-tracking methods and the intraoperative measurement of the same patient. We used the Bland-Altman analysis to show the agreement between the two measurements. The results are expressed as mean $\pm$ standard deviation. $P < .05$ was considered statistically significant.

Results

The results of the sonographic measurements and intra-class correlation are summarized in Figure 3. In the excursion of the tendon or subsynovial connective tissue, we did not find any differences between patients and controls. The shear index, however, was on average 47.8, versus 36.3 in controls ($P < .05$). The maximum velocity ratio in extension was lower for patients than for controls (0.66 and 0.54, respectively; $P < .05$). There was no difference in the velocity ratio in flexion. The intraclass correlations for intra-rater reliability were variable, ranging from 0.36 for the maximum velocity ratio in flexion to 0.83 for subsynovial connective tissue total excursion measurements.

For the comparison between speckle-tracking and in vivo measurements, we found good intraclass correlation coefficients for shear index and maximum velocity ratio measurements (0.86 and 0.83, respectively). The intra-class correlation coefficients for tendon and subsynovial connective tissue excursion measurements were moderate (0.44 and 0.67, respectively). The Bland-Altman analyses (Figure 4) showed a mean difference of -0.30 mm with an SD of 0.57 mm for tendon excursion. For subsynovial connective tissue excursion, the mean difference was -0.02 mm (SD, 0.48 mm); for the shear index, -4.62 (SD, 29.79); and for maximum velocity ratio, -0.13 (SD, 0.32). All results remained within the limits of agreement.

Discussion

With this study, we showed that speckle tracking is a potential method to assess the (pathologic) biomechanics of tendons and subsynovial connective tissue within the carpal tunnel, as well as to distinguish between healthy controls and patients with carpal tunnel syndrome. To our knowledge, a method to dynamically assess subsynovial connective tissue motion within the carpal tunnel has not been described previously.

Speckle tracking, a novel technique to track acoustic signals (speckles) from frame to frame throughout a motion, has been primarily used for analyzing cardiac function.^{16,17} Korstanje et al¹⁸ compared speckle-tracking measurements of tendon motion in porcine forelegs and human cadavers to inserted markers, as well as in vivo measurements taking an anatomic landmark as a reference. They found small tracking error rates for all measurements, as well as for their intra-rater reliability. There is, however, a technical difference between their study and the method presented in this study. With their method, a stationary region of interest is manually selected in the tendon, after which the algorithm automatically distributes a selected number of kernels. Then frame-to-frame displacement is estimated using multiple overlapping kernels. In our study, we manually placed 3 markers, which were followed through the motion; the region of interest was therefore not fixed. A stationary region of interest assumes limited deformation, which is applicable to tendons but not to sub-synovial connective tissue, a much more elastic structure.^{2,5} Therefore, the advantage of our method is that it allows one to measure both tendon and subsynovial connective tissue motion, resulting in shear measurements that can be useful in evaluating patients.

An important problem we observed during image analysis was out-of-plane motion of the tendon or subsynovial connective tissue, which caused the speckles to sometimes lose track of the motion direction of both. This occurrence was probably due to the fact that both structures have 3-dimensional motion directions, while speckle tracking is only able to measure 2 dimensions. In the future, the algorithm and image acquisition method need to be improved, taking into account the motion direction as well as the material properties of the different structures.

Clinical Implications

Our results show a lower maximum velocity ratio and a higher shear index in patients, which is most probably caused by altered subsynovial connective tissue movement. Studies have shown that rapid, differential finger motion causes higher shear strain to the subsynovial connective tissue, leading to shear injury.^{6,7,19} Fibrotic subsynovial connective tissue, whether from injury or disease, can cause a delay in initiation of subsynovial connective tissue motion or a decrease in its velocity compared to the tendon, causing a lower velocity ratio as well as less motion of the subsynovial connective tissue and a higher shear between these two structures. We believe these are important results, first because they suggest a role for sonography in the noninvasive assessment of carpal tunnel kinematics in healthy and diseased individuals, and second because such a tool may be helpful in further

refining the prognosis. For example, the degree of impairment of longitudinal motion might correlate with the likelihood of improvement with nonsurgical therapy or with the likelihood of persistent symptoms after surgery, both of which are currently unpredictable.

Dynamically measuring tendon motion within the carpal tunnel has been done before using color Doppler imaging.^{20,21} However, Yoshii et al¹⁴ found in their recent study that speckle tracking showed a better correlation with tendon excursion than Doppler imaging did. With this study, we added to these results that not only are the maximum velocity ratio and shear index well measurable with speckle tracking, but also that there is a significant difference in these parameters between controls and patients with carpal tunnel syndrome, making them possible discriminating parameters. Fibrosis of the subsynovial connective tissue may be related to carpal tunnel syndrome severity as well, in which case the shear index and maximum velocity ratio may be helpful adjuncts to clinical assessment, for example, in patients with clinically diagnosed carpal tunnel syndrome in whom electrodiagnostic test results are normal, a possibility we plan to assess in the future. However, this study was meant as a first step toward using subsynovial connective tissue and tendon motion as a tool to assess carpal tunnel kinematics, and now that we have shown that these measurements are possible and that there is a difference between controls and patients, it remains for future studies to focus on reliability, improved precision, reproducibility between examiners, and possible clinical applications. If this method would be further developed for clinical use, it might be the first noninvasive, quantitative sonographic method to aid in the diagnosis of carpal tunnel syndrome.

Technical Considerations

Our results show that, overall, there is variability in intraobserver reliability for the sonographic measurements. This variability might be due to several factors. A limitation of all sonographic assessments is the operator dependency, specifically with regard to transducer placement and manual placement of the markers during image analysis. We noticed that this technique requires considerable practice on the part of the examiner, especially when it comes to placing the transducer in alignment with the motion direction of the tendon and getting both the tendon and subsynovial connective tissue visualized throughout the whole motion. However, our analyses were all performed by the same examiner, and after the transducer was placed in the correct position, it was fixed into a custom mounting to keep it in place. This way, the investigator was able to focus on image acquisition.

As for the placement of the markers, we tried to minimize variation in placement by determining that the three markers should be on the structure studied and placed about 1 mm apart from each other. This process may have helped in reducing differences in analysis. Even though sonography is known for being an operator-dependent procedure, we were not able to measure inter-rater reliability because of practical reasons. Also, the analyses are very time-consuming, and for the future, it would be useful to modify the software to make it more readily available for everyday clinical use. We are planning a study to search for the optimal settings in both software and the ultrasound hardware in an in vitro validation model.

Limitations

This study had several limitations. First of all, we reported data from a small number of patients. Also, there was a difference in age and sex between the groups. Carpal tunnel syndrome is more frequent in women, with a peak incidence at 45 to 54 years. This trend is represented in our patient group. We did not specifically attempt, though, to age and sex match the control group; as noted above, this population was a sample of convenience.

Because it is possible that subsynovial connective tissue thickening increases normally with age, it is also possible that the higher average age in the patient group caused greater differences in measurements. These differences could then be due in part to the normal aging process and not entirely due to the development of carpal tunnel syndrome. Because carpal tunnel syndrome is usually bilateral, we chose not to consider the less affected or unaffected contralateral hand of those patients who did not have a diagnosis of bilateral carpal tunnel syndrome as another variant of normal. In the future, it would be helpful to do a case-control study to assess the possibility that aging results in subsynovial connective tissue thickening outside the context of carpal tunnel syndrome.

In addition, as noted before, we found that the settings used in this study are not yet optimal. By optimizing the settings for better sensitivity of the velocity tracking and the excursion measurements, we hope to make a step forward toward developing a noninvasive method to assess the biomechanics and possibly to aid in the evaluation of early-stage carpal tunnel syndrome, in which the subsynovial connective tissue is structurally abnormal but the nerve is not. Finally, our measurements are not fully refined, and the failure to show any differences between the groups for certain parameters may simply have been because the method is currently too imprecise. We therefore need to compare this method with other standardized methods in the future, including the need to assess inter- and intra-examiner reliability.

Conclusions

This study shows that speckle tracking is a new noninvasive method to measure tendon and subsynovial connective tissue mechanics in the human carpal tunnel, with enough accuracy in maximum velocity ratio and shear index measurements to distinguish between healthy individuals and patients with carpal tunnel syndrome. This method may have clinical utility in the future and is worthy of further study.

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Figure 1.
Example of subsynovial connective tissue (SSCT) velocity measurements using speckle tracking analyzed with Syngo VVI software.

Figure 2.
Intraoperative setting with surgical markers on the flexor digitorum superficialis tendon (1) and synovium (2) and a reference marker on the retinaculum (3).

Figure 3. Summary of tendon and subsynovial connective tissue velocity and excursion measurements with speckle tracking in controls and patients with carpal tunnel syndrome (* $P < .01$). CI indicates confidence interval.

Figure 4.

Bland-Altman comparative analysis of the mean and difference between speckle tracking (ST) and in vivo (IV) measurements. MVR indicates maximum velocity ratio; and SSCT, subsynovial connective tissue.