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Shear Strain and Motion of the Subsynovial Connective Tissue and Median Nerve During Single Digit Motion

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Abstract

Purpose—The objective of this study was to measure the relative motion of the middle finger flexor digitorum superficialis tendon, its adjacent subsynovial connective tissue, and the median nerve during single digit motion within the carpal tunnel in human cadaver specimens, and estimate the relative motions of these structures in different wrist positions.

Methods—Using fluoroscopy during simulated single digit flexion, we measured the relative motion of the middle finger flexor digitorum superficialis (FDS) tendon, subsynovial connective tissue and median nerve within the carpal tunnel in twelve human cadavers. Measurements were obtained for three wrist positions: neutral; 60 degrees flexion; and 60 degrees extension. After testing with an intact carpal tunnel was completed, the flexor retinaculum was cut with a scalpel and the same testing procedure was repeated for each wrist position. The relative motions of the tendon, subsynovial connective tissue and median nerve were compared using a shear index, defined as the ratio of the difference in motion along the direction of tendon excursion between two tissues divided by tendon excursion, expressed as a percentage.

Results—Both tendon-subsynovial connective tissue and tendon-nerve shear index were significantly higher in the 60 degrees of wrist flexion and extension positions, compared to the neutral position. After division of the flexor retinaculum, the shear index in the 60 degrees of wrist extension position remained significantly different, compared to the neutral position.

Conclusions—In summary, we have found that the relative motion between a tendon and subsynovial connective tissue in the carpal tunnel is maximal at extremes of wrist motion. These positions may predispose the subsynovial connective tissue to shear injury.

Keywords

Carpal Tunnel; Subsynovial Connective Tissue (SSCT); Median Nerve; Fluoroscopy; Human Cadaver

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INTRODUCTION

Among patients with carpal tunnel syndrome (CTS), the most characteristic histological finding is non-inflammatory fibrosis and thickening of the subsynovial connective tissue (1-3). The subsynovial connective tissue in the carpal tunnel is highly specialized, and provides a supportive framework for tendon gliding and nutrition (4,5). Fibrosis of the subsynovial connective tissue may alter these supportive functions (2,4,6,7). At the time of open carpal tunnel release in CTS patients, adhesion of the median nerve to the subsynovial connective tissue and limited median nerve gliding is often observed (6-8).

Although the epidemiology of hand and wrist repetitive motion related injuries has been reviewed extensively (9-12), little is known about the mechanisms by which these motions might cause CTS. One hypothesis to explain the connection of hand and wrist motion to pathological changes in CTS is that these motions produce a shearing injury to the subsynovial connective tissue. However, while several studies have assessed the displacement of the flexor tendon and median nerve during finger and wrist motion (13-16), to date little has been written regarding the relative motion of the subsynovial connective tissue in the carpal tunnel.

Ettema et al. (8) have introduced a video method to measure the gliding motion of the middle finger FDS tendon and subsynovial connective tissue in an open carpal tunnel, and reported that the subsynovial connective tissue motion relative to middle finger FDS tendon motion differed in CTS patients as compared to unaffected controls. More recently, a method to measure the relative motion of flexor tendon, subsynovial connective tissue median nerve and flexor retinaculum fluoroscopically has been described (17). This method has the advantage that it can be used to view motion within an intact carpal tunnel. The objective of this study was to use this fluoroscopic method to characterize the relative motion of the flexor tendon, subsynovial connective tissue and median nerve within the carpal tunnel in various wrist positions. This data could then be used to estimate the potential risk of shear injury to at the subsynovial connective tissue in these positions.

MATERIAL AND METHODS

This study protocol was approved by our Institutional Review Board. A review of available premortem medical records was performed on cadavers donated to our institution, to obtain clinical and demographic data. Cadaver specimens were excluded if there was a history of carpal tunnel syndrome or other peripheral nerve disease, as well as conditions potentially associated with peripheral nerve disease or carpal tunnel syndrome, including diabetes or glucose intolerance, thyroid disease, rheumatoid arthritis, osteoarthritis, gout, hemodialysis, sarcoidosis, amyloidosis, or traumatic injuries to the ipsilateral arm. Twelve fresh frozen upper extremity specimens without exclusion criteria (six male, six female, aged 45 to 91, mean 78.9 years) were amputated approximately 15 cm proximal to the wrist joint, and were thawed at room temperature prior to testing. Specimens were allowed to equilibrate at room temperature prior to testing, so that the temperature of the specimens was consistent across all testing.

The experimental procedure has been described previously (17). In brief, a custom designed external fixator was used to position the wrist. The specimen was mounted in the fixator by clamping the proximal ends of the radius and ulna. Each hand was mounted palmar side up (Fig. 1-A). A skin incision was made longitudinally to expose the middle finger FDS tendon from the muscle tendon junction to the proximal end of the finger flexor sheath, with the flexor retinaculum and bursa intact. A rectangular window (about 4mm in the longitudinal direction and 5 mm in the transverse direction) was made in the flexor retinaculum to expose the median nerve and subsynovial connective tissue (Fig. 1-B). Two metal markers with a diameter of 1.4-1.6 mm (9291K12, McMaster-Carr, Chicago, IL) (Fig. 1-C) were inserted into the middle

finger FDS tendon and median nerve. A third marker was glued on the surface of the subsynovial connective tissue. The carpal tunnel was otherwise left undisturbed. The proximal ends of the middle finger FDS tendons were fixed with sutures to a Dacron cord and connected to a custom made actuator (RSR12VM, THK America, Inc., IL, MDrive 17, IMS, Inc., CT). A 1N weight was attached to each fingertip to maintain tension in the system (Fig. 1-A). The vertical position of the fingertip weights was changed according to the wrist position, in order to maintain the finger in a standard position of full extension at the start of testing.

Before testing, the normal FDS tendon excursion of the middle finger was determined by passive full metacarpophalangeal joint (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joint flexion/extension. A dead weight (5 N) was attached to the proximal end of the tendon. A mark was applied on the surface of the tendon at the proximal edge of the flexor retinaculum with a surgical marking pen. Then the finger was passively flexed, and the displacement of the mark was measured from the 0 degree finger extension position to the full finger flexion position, using a ruler with a mm scale.. This tendon excursion measurement for each position was used to pre set for the mechanical actuator excursion.

Testing was randomly performed in three different wrist positions, namely, neutral (0 degrees extension), 60 degrees of flexion (Flex 60), and 60 degrees of extension (Ext 60) for each specimen. The middle finger FDS tendon was pulled in a proximal direction by the actuator against the fingertip weight at a rate of 2.0 mm/s until the normal tendon excursion was achieved. This movement of the tendon toward the actuator was regarded as isolated middle finger flexion. Throughout testing, the specimens were kept moist by spraying saline solution. The motion of the three metal markers was recorded from lateral view fluoroscopy (BV 25, Scopifix MDPM, Philips) using a digital video camera (DCR-TRV350, Sony, Japan) (Fig. 2-A, B). A ten millimeter ruler was included in the camera field, in the same plane as the specimen, to scale the distance measurement obtained from the image acquisition. Before data collection, the displacement was observed for two conditioning runs, to confirm repeatability. Data was then collected on the third run. In all cases, the rest of the third run was similar to that of the first two. Each of the marker movements (tendon, subsynovial connective tissue, median nerve) was digitized with Analyze Software (Biomedical Imaging Resource, Mayo Clinic, Rochester, MN) (Fig. 2-C). In addition, the proximal and distal edges of the fixator were digitized as fixed reference points. After testing with an intact carpal tunnel, the flexor retinaculum was cut with a scalpel (simulated carpal tunnel release). The skin was then closed with interrupted sutures. Then the same testing procedure was repeated for each wrist position

Digitized coordinate data (X, Y) for the metal markers on the tendon, subsynovial connective tissue, and median nerve were processed using a custom Matlab program (The Mathworks, Inc, Natick, MA). All coordinate data were converted from pixels to millimeters using the scale factor conversion obtained from the imaged ruler. The coordinates for the tendon, subsynovial connective tissue, and median nerve were normalized relative to the external fixator to correct for any translational or rotational motion of the image or specimen during data collection. Finally, the coordinates of the tendon, subsynovial connective tissue, and median nerve were transformed to a new coordinate system such that the transformed X axis was aligned with the motion direction of the tendon, as defined by a linear polynomial fit to the tendon time series data (Fig. 2-D). 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, subsynovial connective tissue and nerve, the distances along the motion direction of the tendon excursion were calculated. The relative motion between tendon, subsynovial connective tissue and nerve, was compared using a shear index, defined as the ratio of the difference in motion along the direction of tendon excursion between two tissues divided by tendon excursion, expressed as a percentage. For example, the tendon-subsynovial connective tissue shear index would be defined as:

$$[(\text{tendon excursions} - \text{subsynovial connective tissue excursion}) / \text{tendon excursion} \times 100(\%)]$$

In addition, to estimate the potential shear strain during tendon motion, the motion patterns of the subsynovial connective tissue and nerve relative to the tendon excursion were calculated. The maximum tendon excursion was defined as 100%, and the percentage of the subsynovial connective tissue and median nerve motion relative to tendon excursion were measured at each 10% increment (decile) of tendon excursion.

Statistical Analysis

The different wrist positions and the conditions before and after carpal tunnel release were compared for each marker motion and shear index. A mixed linear model was used where each individual specimen was considered as a repeated factor. All results were expressed as mean (standard deviation, SD). The wrist position or carpal tunnel release factors were considered statistically significant when the p-value was less than 0.05 in a full model setting.

A post hoc pairwise comparison was adapted using Scheffe's test criteria for three combinations of wrist position factors (Neutral vs. Flex 60, Neutral vs. Ext 60, Flex 60 vs. Ext 60) where carpal tunnel release factor is controlled. Thus, a p-value less than 0.017 (0.05/3) was considered statistically significant for each of these three pairwise comparisons. All the analyses were conducted using SAS/STAT version 9.1 software (SAS Institute, Cary, NC).

RESULTS

Summary results of displacement for each marker are shown in Figure 3. For tendon excursion, there was a significant increase with wrist extension and a significant decrease with wrist flexion, compared to the neutral position, for both the intact and open carpal tunnel conditions. For subsynovial connective tissue and median nerve excursions in intact wrists, there were significant decreases in the wrist flexion and extension positions compared to the neutral position. After division of the flexor retinaculum, the excursions in the subsynovial connective tissue and median nerve between the wrist flexion position and the wrist neutral position were no longer significantly different. The subsynovial connective tissue motion did show a significant difference in wrist flexion position before and after carpal tunnel release.

Summary results for the shear index are shown in Figure 4. The shear indices of both tendon-subsynovial connective tissue and tendon-nerve were greatest in wrist extension. For the intact carpal tunnel state, the shear indices of both tendon-subsynovial connective tissue and tendon-nerve in the wrist flexion and extension positions were significantly higher than that of the wrist in neutral position. There was a significant decrease in the tendon-subsynovial connective tissue shear index in wrist flexion after carpal tunnel release when compared to intact wrist ($P < 0.05$).

Summary results of the motion pattern analysis are shown in Figures 5 and 6. For subsynovial connective tissue motion with an intact flexor retinaculum, there were significant decreases from the 7th decile of total tendon excursion in the wrist extension position compared to the neutral position. After division of the flexor retinaculum, the subsynovial connective tissue motion in the wrist flexion position increased, with significant differences between the wrist flexion and neutral positions from the 1st to 5th deciles, and wrist flexion and extension positions from the 3rd to 10th deciles of tendon excursion. There were significant decreases from the 6th to 10th deciles in the wrist extension position when compared to the neutral position. There was a significant difference in the first decile of tendon excursion in wrist flexion position before and after carpal tunnel release ($P < 0.05$).

For median nerve motion with an intact flexor retinaculum, there was a significant decrease at the 10th decile of tendon excursion in the wrist extension position compared to the neutral position. After division of the flexor retinaculum, there was a significant decrease position from the 7th to 10th deciles of tendon excursion when comparing the wrist extension and neutral positions. There were also significant differences from the 2nd to 9th deciles of tendon excursion when comparing wrist extension and wrist flexion. There was a significant difference in the 3rd decile of tendon excursion in wrist flexion position before and after carpal tunnel release ($P<0.05$).

DISCUSSION

A previous study reported the effects of wrist position on the displacement of flexor tendon, subsynovial connective tissue and median nerve, and the shear index among those structures with simulated fist motion (17). During single digit motion, the displacement of the subsynovial connective tissue and median nerve for a given tendon excursion were less than the corresponding motions reported for fist motion. This resulted in higher shear indices for single digit motion. We believe that this is because with single digit motion the subsynovial connective tissue is tethered by the adjacent non-moving tendons, limiting the ability of the subsynovial connective tissue to move. This in turn may result in increased force necessary to induce a specific tendon excursion, as noted by Zhao et al (18).

The shear index is a normalized measure of the relative motion of different tissues. This is not a direct measure of shear strain. However, because the motive force was applied to the tendon, we know that the markers on the surface of the visceral synovium and nerve can only move by traction from the intervening subsynovial connective tissue. Assuming that the subsynovial connective tissue is “at rest” before motion of the tendon begins, then the difference between tendon motion and the motion of the markers on the nerve and visceral synovium must represent the displacement occurring within the subsynovial connective tissue. In order to calculate shear strain we would need to know the resting length and orientation of the fibers within the subsynovial connective tissue. Since we do not know this data for our specimens (it can be measured, but only by destructive tests, and thus cannot be known before testing), we can only use this index as a rough guide to the stretch occurring with the subsynovial connective tissue. However, we also believe that it is reasonable to assume that, as the orientation of the fibers within the subsynovial connective tissue is unlikely to change with tendon movement, the shear index is likely to correlate well with the shear strain experienced by the subsynovial connective tissue. To confirm the repeatability of the analysis, in a pilot study we tested each position for five times, and found very similar excursions. In digitizing, we confirmed that the potential error in the tendon motion for a given specimen was less than 0.50 mm. This was considered acceptable for the excursions we were observing, of roughly 30mm. Although the method we used to estimate the potential shear strain is different from the method previously introduced (13,16,19), we believe that the shear index may be useful for applications in situ, such as in vivo, for example to estimate shear during certain activities.

The results of motion pattern analysis suggested that single digit motion in wrist extension that approaches full tendon excursion, such as bending one finger while keeping the others extended, maximizes stretch of the subsynovial connective tissue, and therefore the risk of shear injury. This is in contrast to the findings reported for combined finger flexion, in which the shear index was maximal in wrist flexion (17). This is in part due to differences in Y axis motion. With only one digit moving, Y axis motion is less than it is with all digits moving. This suggests that the effect of flexor retinaculum integrity on the shear index is smaller for single digit motion than it would be for fist motion. Since the role of the flexor retinaculum in restraining Y axis motion only occurs in wrist flexion, this suggests that the flexor retinaculum has a greater effect on the shear index in wrist flexion. This is logical, as in flexion the tendons,

subsynovial connective tissue and nerve are displaced anteriorly towards the retinaculum, whereas in extension they are displaced dorsally and not contact the retinaculum. This in turn suggests that the finger motions likely to induce the most shear may be different between wrist extension and wrist flexion.

The limitations of this study should be noted. First, this was a cadaver study. The results may be different in vivo, where the hydrostatic pressure conditions may be different. There also may be differences in the material properties or mechanical behavior of the tendon and subsynovial connective tissue at 37 degrees C as compared to room temperature. Second, we only measured middle finger FDS tendon motion; we did not test for the other FDS or FDP tendons. The reason we chose the middle finger FDS tendon was because it is anatomically closest to the median nerve, and has been used in other studies (8,18,20). Third, the relative motion was measured with the tendons moving at a speed of 2mm/s. Other speeds were not tested. It is possible that tendon velocity may affect subsynovial connective tissue motion and therefore shear strain (20), especially since the tissues studied are likely to be viscoelastic. Fourth, we only tested static wrist positions, and did not consider cases in which the wrist and tendons move simultaneously. Fifth, we did not consider the effect of motion in the transverse plane. Finally, we also needed to create a small window in the flexor retinaculum to insert the markers. While the markers could be embedded in the tendon and nerve and thus may be unlikely to impede motion, the marker on the subsynovial connective tissue surface may have impeded subsynovial connective tissue motion, especially in the intact carpal tunnel condition.

The strength of this study lies in the detailed information provided on the motion of subsynovial connective tissue and median nerve relative to tendon motion in normal human cadaver hands, which may be important baseline data for the analysis of subsynovial connective tissue function in patients with disorders that affect the subsynovial connective tissue, such as CTS.

In conclusion, we investigated the potential shear strain and motion pattern during single digit motion in cadaver hands in different wrist positions, with and without carpal tunnel release. We demonstrated that 60 degrees of wrist extension maximize both the tendon-subsynovial connective tissue and tendon-nerve shear indices. Carpal tunnel release reduces the shear index in flexion but not in extension. Thus, with or without carpal tunnel release, wrist extension maximized the shear index and, perhaps, the risk for shear injury of the subsynovial connective tissue with differential finger motion. Future studies will be directed toward assessing the effect of the speed of tendon motion on subsynovial connective tissue shear, the effect of motion in three dimensions, and to measuring this shear index in CTS patients.

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(A)

(B)

(C)

Figure 1. Experimental setting

(A) Schematic drawing of experimental setting (modified from the original illustration (17). Copyright Mayo Foundation)

1. Actuator, 2. Custom Fixture, 3. External Fixator, 4. Fluoroscopy, 5. Weight.

(B) Marker placement. 1. Tendon, 2. Median nerve, 3. Subsynovial connective tissue.

(C) Markers. 1. 1.4 mm diameter, 2. 1.6mm diameter.

Initial position

Final position

(A)

Initial position

Final position

(B)

Figure 2. Example of analytic process

1. Tendon, 2. Median nerve, 3. Subsynovial connective tissue, 4. Ligament, 5. Ruler.

(A) Fluoroscopic image.

(B) Schematic drawing of marker motion (from (17). Copyright Mayo Foundation).

(C) The trace for each marker.

(D) Converted coordinates. The tendon motion direction was considered to be the X-axis. The dotted line shows the original axis of tendon motion. The arrows show the tendon motion direction.

Figure 3. Displacement for each marker
 * Significant difference ($p < 0.017$).

Figure 4. Shear index

* Significant difference ($p < 0.017$).

Figure 5. Subsynovial connective tissue motion pattern

(A) Intact carpal tunnel. (B) After release carpal tunnel.

- 1: Significant difference in comparison between Neutral and Ext 60. ($p < 0.017$).
- 2: Significant difference in comparison between Neutral and Flex 60. ($p < 0.017$).
- 3: Significant difference in comparison between Ext 60 and Flex 60. ($p < 0.017$).

Figure 6. Median nerve motion pattern

(A) Intact carpal tunnel. (B) After release carpal tunnel.

- 1: Significant difference in comparison between Neutral and Ext 60. ($p < 0.017$).
- 2: Significant difference in comparison between Neutral and Flex 60. ($p < 0.017$).
- 3: Significant difference in comparison between Ext 60 and Flex 60. ($p < 0.017$).