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In vivo tissue interaction between the transverse carpal ligament and finger flexor tendons

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ABSTRACT

The transverse carpal ligament (TCL) is a component of the flexor pulley system of the wrist, keeping the flexor tendons in place by resisting their volar displacement. The purpose of this study was to investigate the *in vivo* biomechanical interaction between the TCL and flexor tendons in response to tendon tensioning with the wrist at various postures. In eight healthy subjects, the flexor digitorum superficialis and profundus tendons were tensioned by isometrically applying loads (5, 10, and 15 N) to the index finger while the wrist posture was at 20° extension, neutral, 20° flexion, and 40° flexion. The TCL and flexor tendons were imaged at the distal carpal tunnel cross section using ultrasound. The volar-dorsal positions of the tendons, TCL arch height, and TCL-tendon distances were calculated. With increasing wrist flexion, the flexor tendons moved volarly, the TCL arch height increased, and the TCL-tendon distances decreased, indicating that the flexor tendons contacted the TCL and pushed it volarly. The TCL-tendon interaction was amplified by the combination of finger loading and wrist flexion. This study provides *in vivo* evidence of the biomechanical interaction between the TCL and flexor tendons. Repetitive TCL-tendon interactions may implicate the interacting tissues and the median nerve resulting in tissue maladaptation and nerve compression.

1. Introduction

The carpal tunnel is a passageway within the wrist for the median nerve and flexor tendons. The tunnel is bordered laterally, dorsally, and medially by the carpal bones, and volarly by the transverse carpal ligament (TCL). Passing through the carpal tunnel are nine flexor tendons for the flexor pollicis longus of the first digit and the flexor digitorum superficialis (FDS) and flexor digitorum profundus (FDP) of the second through fifth digits. The digital flexor tendons facilitate joint motion by transmitting a force, from the flexor muscles to their bony attachments, about each joint. Tensioning of the flexor tendons results in their migration in the transverse plane of the carpal tunnel [1,2], moving volarly with wrist flexion and dorsally with wrist extension [3,4].

The flexor tendons can biomechanically interact with their surrounding structures when they move in the carpal tunnel. Previous studies have focused on the interaction between the flexor tendons themselves or between the tendons and the median nerve [5–11]. However, the interaction between the flexor tendons and the TCL remains unclear. The TCL provides mechanical advantages for the flexor tendons, acting as a pulley for the tendons during wrist flexion [12] and maintaining the moment arms of the flexor tendons at the wrist to prevent bowstringing [13]. The functional role of the TCL brings about a biomechanical interaction between the ligament and the tendons. Implications of this tissue interaction have been suggested by histological adaptation of carpal tunnel tissues [14] and by the altered movement of the flexor tendons after transection of the TCL in carpal tunnel release surgery [13,15].

Tissue interactions inside the carpal tunnel may implicate the median nerve as a result of direct mechanical contact and/or tissue remodeling. As the flexor tendons move towards the TCL, they may compress the median nerve situated between the tendons and ligament. Furthermore, the repetitive TCL-tendon interactions may lead to maladaptation of the carpal tunnel structure and its contents, culminating in the onset of carpal tunnel syndrome. For example, carpal tunnel syndrome has been associated with pathological changes of the TCL [16–18] and tenosynovium [17,19,20].

Despite the clinical implication of the interactive carpal tunnel components, the explicit TCL-tendon interaction is unclear. Therefore, the purpose of this study was to investigate the *in vivo* biomechanical interaction between the TCL and flexor tendons in response to tensioning of the finger flexor tendons while the wrist assumed different postures. In this study, the biomechanical

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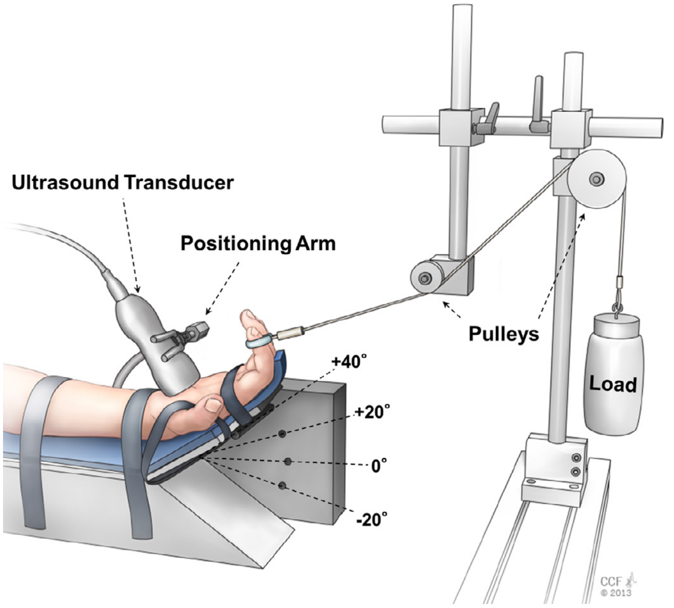

Fig. 1. Experimental setup for ultrasound imaging at the distal carpal tunnel level while the wrist assumed a specific posture and the index finger was loaded.

interaction was determined based on the relative positions of the tendons and the TCL; for example, an increased interaction would be indicated by the volar migration of the flexor tendons, increased TCL arch height, and decreased TCL-tendon distances. It was hypothesized that increased tendon tension and wrist flexion would result in an increased biomechanical interaction between the TCL and flexor tendons.

2. Methods

2.1. Human subjects

Eight healthy, right-handed female subjects (age 26.9 ± 7.1 years) participated in this study. Individuals were excluded if they had any history of trauma or musculoskeletal/neuromuscular disorders affecting the right hand or wrist. The study procedures were approved by the local Institutional Review Board and written informed consent was provided prior to participation.

2.2. Experimental setup

Each subject sat next to a testing table with the right shoulder abducted 30° and elbow flexed 90°. The right hand was supinated and secured to a custom apparatus that was designed to statically load the index finger while maintaining the wrist in various postures (Fig. 1). The index, middle, ring, and little fingers were stabilized at the metacarpophalangeal joints and placed in a slightly flexed posture at the interphalangeal joints, while the thumb was abducted 30° in the palmar plane. The index finger was further positioned to ensure that its pad was perpendicular to the palm of the hand. A wire was looped around the index finger pad and redirected over the two adjustable pulleys of the custom apparatus. The wire's line of action, from the index finger to the nearest pulley, was parallel to the palm of the hand.

2.3. Experimental procedures

The index finger of each subject was loaded to tension its FDS and FDP tendons while the wrist was positioned in 20° extension (−20°), neutral (0°), 20° flexion (+20°), and 40° flexion (+40°). The wrist postures were tested in a randomized order across subjects. Within each wrist posture the index finger was loaded, in randomized order, with 5 N, 10 N, and 15 N. The loads correspond to 10–50% of the maximal force of the index finger [31]. Each load was applied for 5 seconds via the wire looped around the index finger pad. For each posture-load condition, three trials were collected and a one-minute rest was provided between consecutive trials.

Ultrasound imaging of the distal carpal tunnel cross section was performed to capture the TCL and index finger flexor tendons under each posture-load condition. An ultrasound system (Acuson S2000 Siemens Medical Solutions USA, Mountain View, CA) with a linear array transducer (9L4, Siemens Medical Solutions USA, Mountain View, CA) was used with an imaging frequency of 7 MHz, a depth of 3 cm, tissue harmonic imaging, and tissue equalization. A thick layer of ultrasound gel was placed on the palm of each subject at the distal carpal tunnel level; this thick gel layer was used to minimize the amount of force applied onto the palm by the transducer so as to avoid inadvertently influencing the morphology of the carpal tunnel. The transducer was oriented perpendicularly to the palm and adjusted so that the hook of the hamate, ridge of the trapezium, TCL, and index finger FDS and FDP tendons were clearly distinguishable on the ultrasound image. A positioning arm was used to stabilize the transducer's position throughout the experiment. For each trial, a 10 s ultrasound video was captured. The ultrasound video was initiated when no load was applied to the index finger (0 N condition) and then 5-s after initiating the video the index finger was loaded with the predetermined load for 5 s. Ultrasound imaging was performed by a single operator (JLG) and the ultrasound videos were captured at a rate of 42 frames/s.

2.4. Data processing

Two image frames were extracted from each ultrasound video: (1) an image from the first 5 seconds of the video when the finger was unloaded (0 N condition) and (2) an image from the last 5 seconds of the video after the finger was loaded (5 N, 10 N, or 15 N condition). For each extracted image, the polygon tool in *ImageJ* (National Institutes of Health, Bethesda, MD) was used to manually trace the boundary of the FDS and FDP tendons of the index finger, and to determine the coordinates of each tendon's centroid. Then, the volar and dorsal boundaries of the TCL were manually selected using the *ImageJ* multi-point tool to determine their respective coordinates. Furthermore, the coordinates of most volar points of hook of the hamate and ridge of the trapezium were identified.

The obtained coordinates were used as inputs into a custom *MATLAB* program (Mathworks, Natick, MA). First, the program established an anatomical coordinate system whose x-axis (medial-lateral axis) was along the line connecting the hook of the hamate and ridge of the trapezium bony landmarks and whose y-axis (dorsal-volar axis) was the perpendicular bisector of the line between these two points (Fig. 2). Then, the program transformed the coordinates identified in *ImageJ* to the defined anatomical coordinate system and calculated the outcome parameters. The outcome parameters were (1) FDS and FDP tendon positions, (2) TCL arch height, and (3) TCL-FDS and TCL-FDP distances. The FDS and FDP tendon positions were determined as the dorsal-volar location of each tendon's respective centroid. The TCL arch height was defined as the distance between the apex of the TCL's volar boundary and the x-axis. The TCL-tendon distance was calculated as the distance in the dorsal-volar direction between each tendon's centroid and the dorsal boundary of the TCL.

2.5. Statistical analysis

Two-way (4 × 4) repeated measures ANOVAs were performed to determine the effects of wrist posture (−20°, 0°, +20°, +40°) and