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Quantification of the transverse carpal ligament elastic properties by sex and region

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ABSTRACT

Background: The transverse carpal ligament is an integral factor in the etiology of carpal tunnel syndrome. The purpose of this study was to report the biomechanical properties of this ligament and quantify sex-based differences and regional variation in tissue response. We hypothesized that the mechanical response would not be uniform across the surface, and that female ligament properties would have higher strain profiles and lower mechanical properties.
Methods: Uniaxial testing of twelve (six males, six females) human fresh frozen cadaveric transverse carpal ligaments was carried out using an Instron Materials Testing Machine. Strain was measured via a non-contact optical method.
Findings: The following biomechanical properties of the transverse carpal ligament were reported in this work: failure strain (male: 9.2 (SD 5.0), female: 15.5 (SD 7.1)%), strength (male: 4.9 (SD 1.5), female: 4.5 (SD 1.6) MPa), and modulus of elasticity (male: 52.9 (SD 19.6), female: 38.2 (SD 21.9) MPa). The radial side displayed significantly more strain at failure compared to ulnar ($P < 0.0001$).
Interpretation: The results of this study provide evidence that manipulative treatments should focus stretching on the radial half of the tissue, which experiences larger strains under uniform loading conditions. In addition, this work suggests possible sex-based differences in mechanical properties of the transverse carpal ligament, which could provide a basis for the development of improved non-surgical treatment methods for carpal tunnel syndrome. The results can also be applied to generate more accurate computational models of the wrist.

1. Introduction

Carpal tunnel syndrome (CTS) is the most common entrapment neuropathy, affecting approximately 3.8% of the adult population (Uchiyama et al., 2010). CTS develops when increased pressure inside the carpal tunnel compresses the median nerve, resulting in numbness, tingling or burning sensations in the hand (Tsujii et al., 2009). It has been consistently noted that women are more susceptible to developing CTS than men by approximately a factor of two; however, an explanation for this has not been established (Atroshi et al., 1999; Foley et al., 2007; Manktelow et al., 2004). The transverse carpal ligament (TCL) forms the volar boundary of the carpal tunnel. It is thought to contribute to carpal stability, provide an anchor to the hypothenar and thenar muscles, and act as a component of the flexor tendon pulley system (Guo et al., 2009; Lluch, 2007; Xiu et al., 2010). The TCL is delineated by its bony attachments to the hamate, scaphoid, trapezium and pisiform and is contained within the flexor retinaculum. Accurate biomechanical properties of this ligament are necessary to improve existing computational models of the wrist, evaluate possible non-invasive treatment options, as well as gain insight into the etiology of CTS.

While several studies have examined the biomechanical properties of the TCL, varying testing approaches have been used including indentation testing (Holmes et al., 2011; Li, 2005; Main et al., 2012), uniaxial testing (Garcia-Elias et al., 1989), biaxial testing (Holmes et al., 2012), and hanging weights (Lin et al., 1983; Xiu et al., 2010). These widely varying methodologies make comparison of the results between studies, as well as implementation of the resulting properties into computational models, difficult. Moreover, computational or finite element models of the wrist (Gislason et al., 2012; Gislason et al., 2010; Guo et al., 2009; Troy et al., 2007) require either

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the tissue stiffness or elastic modulus to define the mechanical response. The testing methods used above have not provided either of these quantities. As a result, previous models of the wrist have either not referenced the source of the TCL properties (Gislason et al., 2012), not included the TCL (Troy et al., 2007), or estimated the TCL properties based on published values of neighboring ligaments (Gislason et al., 2010; Guo et al., 2009). From the perspective of measurement of carpal tunnel volume or effects of carpal tunnel surgery via finite element methods, accurate properties of all the soft tissues surrounding the tunnel, especially the TCL which constitutes the entire volar border, may play a critical role.

Current literature suggests that the TCL does not strain uniformly under tensile load. It has been reported that proximal/distal variations in tissue response exist (Holmes et al., 2012; Xiu et al., 2010), however, ulnar/radial variations have yet to be quantified. A study by Kung et al. (2005) reported anatomical variations in the TCL in the ulnar–radial direction, since approximately two thirds of thenar musculature attachments were shown to originate from the radial end while only about half of the hypothenar musculature attachments were shown originate from the ulnar end (Kung et al., 2005). Main et al. (2012) showed via indentation that compressive stiffness of the TCL was lower at locations close to muscle attachments. This suggests a basis for ulnar/radial variation in tensile tissue properties. Quantification of ulnar/radial variation could have important implications for manipulative therapies for CTS given that practitioners apply tensile loads to the TCL in the transverse (ulnar/radial) direction (Siu et al., 2012; Sucher et al., 2005). Specifically, manipulative therapy has been hypothesized to offer benefits including the release of tissue adhesions, increased muscle strength, increased range of motion, and increased length of the TCL resulting in enlarged carpal tunnel volume and subsequently lower intratunnel pressure (Siu et al., 2012). Manipulative therapy (myofascial release) involves restricting motion of the first and fifth digits of the patient, introducing dorsiflexion of the hand, and applying traction to the lateral and medial attachments of the transverse carpal ligament using a 3 or 4 point bending technique (Siu et al., 2012). If the regional response of the TCL was further clarified, these non-surgical CTS treatment methods could be optimized by focusing manipulative stretching to the area with the highest strain capacity. This could accordingly involve increased manipulation on either the ulnar or radial portion of the TCL.

Sucher et al. (2005) reported increases in carpal arch width after manipulative treatment on cadaveric samples with female samples being more responsive to treatment. They noted that at a given force, female TCLs experienced higher initial and residual elongation than male TCLs. It is possible that weaker TCLs make females more responsive to this treatment; however, sex-based differences in carpal mechanics have been minimally investigated. Li (2005) reported differences in carpal compliance between sexes with female carpal tunnels being less compliant during indentation testing. A similar finding by Lin et al. (1983) was also reported. However, Li (2005) tested the carpal complex with overlaying muscle and tissue intact, hence the properties of the TCL were not isolated. Given that carpal tunnel syndrome afflicts twice as many females compared to males (Atroshi et al., 1999), a more detailed sex-based analysis of TCL properties is warranted. Mechanical variation related to gender may have implications to both the success of manipulative treatment options in addition to gaining insight into the possible etiology of the disease.

The purpose of this study was to quantify the uniaxial biomechanical properties of the TCL as well as illuminate any regional and sex-based variation in tissue response. It was hypothesized based on previous studies that female TCL samples would have higher stiffness and greater strain at failure compared to their male counterparts. As well, we hypothesized that mechanical strain distribution would be non-uniform over the surface of the TCL.

2. Methods

2.1. Specimen preparation

The TCL was extracted from twelve fresh-frozen cadaver wrists from six male (average age 84 (SD 10) years) and six female (average age 75 (SD 15) years) donors. Specimens were dissected to include the eight carpal bones, the TCL and its attachments to the scaphoid, hamate, pisiform and trapezium. Samples were stored in a freezer at −20 °C until testing, which has been shown not to alter tissue properties (Woo et al., 1986). In order to obtain the two bony end-blocks necessary for uniaxial testing, the carpal tunnel was separated at the level of the lunate–scaphoid, capitate–trapezoid, and at the second and third metacarpals.

2.2. Experimental protocol

Human ethics approval to conduct this study was obtained from both the University of Toronto as well as the University of Guelph. TCL thickness was measured at nine locations in a grid formation (Fig. 1) using a custom built micrometer. Measurements at each location were repeated five times and an average was taken. An average was then taken across the proximal/distal as well as ulnar/radial rows for later statistical comparison. TCL width was measured using a set of calipers (Mastercraft Toronto, ON) across the ulnar, middle, and radial ends of the tissue.

Cylindrical steel pots for bone fixation were custom built to fit an Instron Universal Testing Machine (Instron Corp., Canton, MA) (Fig. 1). Samples were aligned so that force was applied in the ulnar/radial direction along the known direction of predominant fiber orientation of the TCL (Prantil et al., 2012). The hamate, capitate, and fourth metacarpal were secured with sharpened bolts in one pot, and the scaphoid, the trapezoid and the first metacarpal were secured in the other. The two bony end blocks were then potted in acrylic resin to ensure that no bone movement occurred during testing. Limiting any bone movement was necessary to ensure that the mechanical properties measured where only those of the isolated TCL. A 2-mm Kirschner wire (Fig. 1) was then drilled through the pisiform into the hamate in order to minimize movement during testing as it was not possible to secure this small bone with either the resin or bolts. Nine markers (2 mm lead shot) were then fixed to the specimen using cyanoacrylate cement in a grid formation in order to create a regional strain profile of the TCL (Fig. 1). Markers were placed in the middle of the specimen and along the hook of hamate and the trapezial ridge in order to capture strain across the whole tissue.

The ligament was irrigated with saline solution throughout testing to avoid drying. Before each test, a small preload of 5 N was applied to the tissue to avoid tissue slack during testing. Samples were then preconditioned at 5% strain for 20 cycles at 1 Hz, which demonstrated a stable tissue response through pilot testing. The maximum level of 5% strain corresponds to less than half the expected failure strain and thus at this point in the stress–strain curve, premature failure is unlikely to occur (Schatzmann et al., 1998). Furthermore, Sucher et al. (2005) showed that TCLs subjected to 5% and 7% strain showed no evidence of permanent damage.

Following preconditioning, samples were then subject to a stress relaxation test to 5% strain at a 1 mm/s and allowed to relax for 90 s, which is comparable to other studies of tendons and ligaments (Sverdlik and Lanir, 2002; Vanderby and Lakes, 2010). Finally, the tissue was loaded to failure at a strain rate of 100 mm/min (Johnston et al., 2004). A GRAS-20S4M/C camera system (Point Grey Research Inc., Richmond, BC) was used to record optical strain for this test and was aligned perpendicular to the tissue surface. The acquisition interval for both the computer data acquisition system and the camera were both set at 10 Hz and synchronized.