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Tensile properties of the transverse carpal ligament and carpal tunnel complex

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ABSTRACT

Background: A new sophisticated method that uses video analysis techniques together with a Maillon Rapide Delta to determine the tensile properties of the transverse carpal ligament–carpal tunnel complex has been developed.
Methods: Six embalmed cadaveric specimens amputated at the mid-forearm and aged (mean (SD)): 82 (6.29) years were tested. The six hands were from three males (four hands) and one female (two hands). Using trigonometry and geometry the elongation and strain of the transverse carpal ligament and carpal arch were calculated. The cross-sectional area of the transverse carpal ligament was determined. Tensile properties of the transverse carpal ligament–carpal tunnel complex and Load–Displacement data were also obtained. Descriptive statistics, one-way ANOVA together with a post-hoc analysis (Tukey) and t-tests were incorporated.
Findings: A transverse carpal ligament–carpal tunnel complex novel testing method has been developed. The results suggest that there were no significant differences between the original transverse carpal ligament width and transverse carpal ligament at peak elongation ($P = 0.108$). There were significant differences between the original carpal arch width and carpal arch width at peak elongation ($P = 0.002$). The transverse carpal ligament failed either at the mid-substance or at their bony attachments. At maximum deformation the peak load and maximum transverse carpal ligament displacements ranged from 285.74 N to 1369.66 N and 7.09 mm to 18.55 mm respectively. The transverse carpal ligament cross-sectional area mean (SD) was 27.21 (3.41)mm^2.
Interpretation: Using this method the results provide useful biomechanical information and data about the tensile properties of the transverse carpal ligament–carpal tunnel complex.

1. Introduction

The clinical motivation for this study is carpal tunnel syndrome which is the most common compression and frequently diagnosed peripheral nerve disorder (Pfeffer et al., 1988; Sucher and Schreiber, 2014). The carpal tunnel complex comprises bones, ligaments, muscles, tendons and nerves that are all enveloped under the skin. Within the carpal tunnel complex, the transverse carpal ligament (TCL) along with the hypothenar and thenar muscles are important in the stability of the carpus and form the roof of the carpal tunnel. The volar boundary of the carpal tunnel commonly referred to as the flexor retinaculum comprises a strong band of connective tissue consisting of the proximal thin antebrachial fascia, the middle thick TCL and the most distal aponeurosis between the hypothenar and thenar musculature (Brooks et al., 2003; Cobb et al., 1993; Pacek et al., 2010b). Anatomically, the TCL attaches to the carpal bones distally and proximally. In the distal row, the TCL attaches to the hook of hamate on the ulnar side and ridge of the trapezium on the radial side. In the proximal row, the TCL attaches to the pisiform bone on the ulnar side and tubercle of the scaphoid on the radial side. In addition, the tendons and median nerve together with the TCL form a pulley system (Brooks et al., 2003; Fuss and Wagner, 1996; Stecco et al., 2010). During finger and hand movements the median nerve and tendons move in longitudinal, transverse, and volar/dorsal directions (Lopes et al., 2011; Ugbolue et al., 2005; Yoshii et al., 2008). The median nerve becomes compressed as the carpal tunnel contents move within the carpal tunnel (Armstrong and Chaffin, 1979; Ugbolue et al., 2005).

The TCL has been investigated morphologically (Pacek et al., 2010a) and its collagen fibre orientation has been characterized (Prantil et al.,

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2012). So far although these studies have provided an understanding of the TCL composition and behaviour, more research is still necessary to fully understand the biomechanical properties of the TCL. In terms of biomechanical studies associated with TCL palmar–dorsal loading, the indentation method has been used by various scientific investigators (Chaise et al., 2003; Holmes et al., 2011; Ugbolue, 2012; Ugbolue et al., 2011). Also previous studies have investigated the biomechanical properties of the TCL extracted under biaxial strain (Holmes et al., 2012) and with the TCL intact using manipulation and load bearing techniques (Li et al., 2009; Sucher and Hinrichs, 1998; Xiu et al., 2010). While these methods have involved either excising the TCL or determining the biomechanical properties of the carpal tunnel with the TCL intact/transected, more research designs and testing procedures are necessary to evaluate the TCL and carpal tunnel complex as a whole.

Although dorsally and palmarly directed forces provide insight into the load induced changes to the carpal tunnel morphology, elongating the TCL to failure would inform the 'safe' range of loads that could be clinically applied during attempts to increase the carpal tunnel volume, and thus reduce the pressure within the carpal tunnel. The symptoms are alleviated once the pressure within the carpal tunnel subsides and/or the likely swelling of the carpal tunnel contents is reduced. Currently there are various treatment methods available to help alleviate carpal tunnel syndrome (CTS) symptoms (Zuo et al., 2015). Percutaneous balloon carpal tunnel plasty, invented by Dr J Lee Berger is a novel treatment procedure that involves stretching the TCL. However, from a biomechanical research perspective more research designs and testing procedures potentially could help improve current treatment procedures associated with stretching the TCL and ultimately increasing the volume of the carpal tunnel. The primary weakness of previous methods is not the methodologies but the fact that no testing has been done in terms of elongating the ligament *in situ* to failure.

Our method provides useful information that clearly shows the range of elongation of the TCL and associated changes to the carpal arch width. Also, it provides valuable data pertaining to what the 'safe range' of forces applied to the TCL should be, so as to prevent the likelihood of additional clinical problems such as ligament rupture. Indeed, the lack of a widely accepted method does not diminish the utility of the existing data, instead a standard methodology needs to be established that potentially could be referred to as an acceptable gold standard all researchers can associate with. Thus, despite the valuable input provided by previous studies, experimentally there is still no widely accepted testing method specifically designed to evaluate the tensile properties of the carpal arch (CA) and intact TCL. That is, to date there is no known method that tests the TCL to failure *in situ*. Hence, due to the complexity of the hand and wrist the need has arisen to design and develop a sophisticated method to determine the tensile properties of the carpal tunnel complex. Therefore, this study describes a novel method to determine the tensile properties of the TCL *in situ* using two dimensional video analyses together with a commercial Maillon Rapide Delta (S3i Ltd, Bawtry, England, UK).

2. Methods

The study was approved by the Department of Biomedical Engineering, University of Strathclyde and the Laboratory of Human Anatomy, University of Glasgow departmental ethics committees. All specimens were free from any musculoskeletal and neurological disorders.

2.1. Tensile testing procedure

Six embalmed cadaveric specimens amputated at the mid forearm and aged 82 ± 6.29 years were tested. The six hands were from four individuals (two pairs and two individual hands), three males (four hands) and one female (two hands). The tensile properties of the TCL were determined using a commercial Maillon Rapide Delta (S3i Ltd, Bawtry, England, UK) fastened to a steel work piece (Fig. 1). The Maillon Rapide Delta is similar to a Carabiner and is built to transfer forces.

The Maillon Rapide Delta (S3i Ltd, Bawtry, England, UK) and steel work piece unit were attached to the upper hydraulic tensile grips connected to the 1000 N load cell (Model: Instron E10000 (Instron, Bucks, UK)), of the Instron Materials Testing Machine. The testing machine was operated by a personal computer running the High Load Materials Testing Machine Instron E10000 Bluehill Software package.

Prior to testing, each specimen was prepared by exposing the TCL with carpal tunnel contents removed. The thenar and hypothenar muscles together with all other surrounding soft tissue such as fat and muscle fascia were removed. TCL anthropometric measurements of the specimens were obtained. The lower hydraulic tensile grip was disconnected and removed to provide room for the custom made aluminium specimen platform (Fig. 2).

The custom made aluminium specimen platform was fastened to the base of the Instron E10000 Materials Testing Machine. The specimen was placed on the aluminium platform. The Maillon Rapide Delta (S3i Ltd, Bawtry, England, UK) was looped around the TCL to enable the application of the palmarly directed forces without the TCL slipping free from the device. The Maillon Rapide Delta (S3i Ltd, Bawtry, England, UK) was then attached to the upper hydraulic tensile grips connected to the 1000 N load cell. The hand specimen was lying supinated with the wrist in the neutral position i.e. 0° flexion and 0° extension. The specimen was adjusted until the TCL was aligned and perpendicular to the Maillon Rapide Delta (S3i Ltd, Bawtry, England, UK). Once the specimen was aligned, it was secured in position via three rectangular aluminium bars that were tightened using two M8 threaded bolts and wing nuts per bar. The placement of the three rectangular aluminium bars was standardised. The first bar was placed distal to the palmar digital crease. The second bar was placed proximal to the distal palmar crease and holding down the phalanges of the thumb. The third bar was placed proximal to the wrist crease. The specimens were tightly fastened and secured to the custom made aluminium specimen platform apparatus. This was confirmed when no volar or side to side movements were observed prior to embarking on the preconditioning cycle.

The test protocol started with a preconditioning cycle where the specimen underwent 10 cycles of 0.5 N loading at a rate of 2 Hz. The experimental procedure entailed raising the Maillon Rapide Delta (S3i Ltd, Bawtry, England, UK) and steel work piece unit until contact was made with the inside surface of the TCL and a load of 0.5 N was recorded. The load cell was subsequently tared and a deformation rate of 20 mm/s was used to deform the TCL until a drop off load was detected which was categorized as failure of the ligament. Indeed, this testing procedure being unique had no reference point with regard to a choice of suggested deformation rates. A series of tests were performed in the laboratory prior to arriving at the 20 mm/s deformation rate. A selection of deformation rates were chosen for the pilot test. Upon completion of the testing, a deformation rate of 5 mm/s was too slow. The deformation rate was then doubled to 10 mm/s which again was too slow. For both deformation rates (at 5 mm/s and 10 mm/s) the Maillon Rapide Delta kept on slipping away from the centre of the ligament which was set to be in line with the steel work piece unit attached to the upper hydraulic tensile grips connected to the 1000 N load cell (Model: Instron E10000 (Instron, Bucks, UK)). Once the deformation rate was increased to 20 mm/s the slipping motion of the Maillon Rapide Delta reduced considerably as the soft tissue underwent deformation. Initially, a customised D'Shackle was used to determine the tensile properties of the intact TCL. After a few trials the authors came to realise it was not a good fit for specimens with smaller sized carpal tunnels and TCL lengths greater than 20 mm; hence the Maillon Rapide Delta (S3i Ltd, Bawtry, England, UK) was preferred. This unique approach uses a Maillon Rapide Delta (S3i Ltd, Bawtry, England, UK) attached to a steel work piece that is secured between jaws of the upper hydraulic tensile grips of the Instron E10000 (Instron, Bucks, UK) Materials Testing