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Finite element analysis for transverse carpal ligament tensile strain and carpal arch area

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A B S T R A C T

Mechanics of carpal tunnel soft tissue, such as fat, muscle and transverse carpal ligament (TCL), around the median nerve may render the median nerve vulnerable to compression neuropathy. The purpose of this study was to understand the roles of carpal tunnel soft tissue mechanical properties and intratunnel pressure on the TCL tensile strain and carpal arch area (CAA) using finite element analysis (FEA). Manual segmentation of the thenar muscles, skin, fat, TCL, hamate bone, and trapezium bone in the transverse plane at distal carpal tunnel were obtained from B-mode ultrasound images of one cadaveric hand. Sensitivity analyses were conducted to examine the dependence of TCL tensile strain and CAA on TCL elastic modulus (0.125–10 MPa volar-dorsally; 1.375–110 MPa transversely), skin-fat and thenar muscle initial shear modulus (1.6–160 kPa for skin-fat; 0.425–42.5 kPa for muscle), and intratunnel pressure (60–480 mmHg). Predictions of TCL tensile strain under different intratunnel pressures were validated with the experimental data obtained on the same cadaveric hand. Results showed that skin, fat and muscles had little effect on the TCL tensile strain and CAA changes. However, TCL tensile strain and CAA increased with decreased elastic modulus of TCL and increased intratunnel pressure. The TCL tensile strain and CAA increased linearly with increased pressure while increased exponentially with decreased elastic modulus of TCL. Softening the TCL by decreasing the elastic modulus may be an alternative clinical approach to carpal tunnel expansion to accommodate elevated intratunnel pressure and alleviate median nerve compression neuropathy.

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1. Introduction

The carpal tunnel is formed by the carpal bones and transverse carpal ligament (TCL), providing passage of the median nerve and nine flexor tendons. The mechanical environment of the carpal tunnel is the main determinant for compression neuropathy of the median nerve. Increases in tissue thickness and stiffness of the TCL have been shown in patients with carpal tunnel syndrome (Miyamoto et al., 2013; Marquardt et al., 2016), suggesting the etiological mechanisms of the neuropathy. The mechanical role of the TCL in median nerve compression is also illustrated by carpal tunnel release surgery, in which the TCL is transected to reduce the mechanical constraint of the carpal tunnel as a means of nerve decompression.

Surgical transection of the TCL is a standard treatment for carpal tunnel syndrome. The procedure aims to increase tunnel volume and decrease carpal tunnel pressure by increasing compliance of the volar region, thereby decreasing compression on the median nerve (Okutsu et al., 1989; Kato et al., 1994). Notably, flattening of the median nerve at distal level of the carpal tunnel is increased in patients with carpal tunnel syndrome (Buchberger et al., 1991; Horch et al., 1997) and carpal tunnel release surgery helps reduce the nerve flattening and restore its normal shape (El-Karabaty et al., 2005; Momose et al., 2014). However, persistent weakness of grip and pain over the thenar and hypothenar origins, known as "pillar pain", are common surgical complications. Carpal tunnel release in conjunction with ligament lengthening reconstruction has been proposed to alleviate postoperative pillar pain, improved early grip strength and earlier return of function compared with traditional open carpal tunnel release (Pavlidis et al., 2010; Seitz and Lall, 2013; Saravi et al., 2016).

Carpal tunnel area is strongly dependent on the characteristics of the soft tissues volar to the carpal tunnel. It has been shown that

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carpal tunnel expansion after TCL release surgery is mainly (93%) contributed by the increase in CAA (Kato et al., 1994). In a geometrical model, Li et al. (2009) showed that carpal arch width shortening or TCL elongation is effective in forming a greater arch to gain increased CAA. Thus the increase in TCL tensile strain might be an alternative approach to enlarging the carpal tunnel area. Furthermore, the carpal tunnel is compliant to accommodate physiological variations of carpal tunnel pressure, and an increase in pressure led to greater CAA and carpal tunnel area (Li et al., 2011). Clinically, elevated pressure has been observed in patients with carpal tunnel syndrome (Gelberman et al., 1981). Under pathophysiological intratunnel pressure, carpal arch morphology may be particularly dependent on the mechanical properties of the TCL. Furthermore, tissues (i.e. thenar muscles, skin, and fat) volar to the TCL are a mechanically constraining factor that could also affect carpal arch formation.

Finite element (FE) modeling is an effective tool to perform parametric analyses of different mechanical factors that might be challenging to extrapolate from experimental data. Subject-specific FE models based on medical imaging providing representation of patient-specific anatomy have been utilized in many fields. Specifically for the carpal tunnel, previous FE modeling has been used to examine the effects of TCL release on displacement of carpal bones and contact stress in the midcarpal joints (Guo et al., 2009), and carpal arch enlargement under optimal force direction (Walia et al., 2017). However, carpal tunnel FE modeling has paid little attention to the mechanical properties of the various soft tissues, i.e. skin, fat, and thenar muscles in the volar aspect of the tunnel. The TCL, skin, fat and thenar muscles might constrain the carpal arch through their structural and mechanical interactions. For the carpal tunnel pressure, previous FE modeling has been used to examine the effect of increased carpal tunnel pressure caused by awkward wrist postures on the deformation of median nerve (Mouzakis et al., 2014). The intratunnel pressure might also alter the carpal arch and TCL geometry.

The current study was developed using subject-specific FE model to investigate the biomechanical behavior of the carpal tunnel influenced by mechanical properties of soft tissues including TCL, skin, fat, thenar muscles in the volar carpal tunnel. A comprehensive understanding of the subject-specific carpal arch biomechanics and morphology depends both on subject-specific anatomy and tissue mechanical properties. We developed the model in this study to understand the roles of TCL, skin, fat, thenar muscles mechanical properties and intratunnel pressure on TCL tensile strain and CAA using parametric analysis. It was hypothesized that TCL tensile strain and CAA would increase by decreasing stiffness of TCL, skin, fat, and thenar muscles.

2. Methods

2.1. Cadaveric specimen for ultrasound imaging

One fresh frozen cadaveric hand (male; left; age 74 years; height 177 cm; weight 95 kg) was used in this study. The specimen had no hand injury, surgery, or musculoskeletal disorders to the hand or upper extremity. The specimen was thawed overnight at room temperature prior to experimentation. The specimen was positioned in a supinated, anatomically neutral position at the wrist with all fingers naturally curled (Fig. 1a). High frequency (17 MHz) B-mode ultrasound images were captured at the distal carpal tunnel using an ultrasound system (ACUSON S2000, Siemens Medical Solutions USA, Inc., Mountain View, CA, USA). A linear array 18L6 HD transducer was aligned at the transverse plane of distal carpal tunnel along the line connecting hook of hamate and ridge of trapezium (Fig. 1a). The depth of the image field was 2.5 cm with image resolution as 0.0624 mm/pixel and gain as 8 dB.

2.2. Subject-specific finite element modeling

The contours of thenar muscles, skin, fat, TCL, volar boundary of hamate bone and trapezium bone (Fig. 1b) were extracted with manual segmentation using the grey value threshold in ImageJ 1.46r (US National Institutes of Health, Bethesda, USA). With a thickness of 1 mm, a pseudo-three dimensional (3D) volar carpal arch structure was reconstructed using solid modeling (SolidWorks 2012, Dassault Systems, Waltham, MA, USA) and then exported to finite element (FE) software ABAQUS CAE (v6.10, Simulia, Providence, RI, USA) for FE analysis. The model components included hamate bone, trapezium bone, thenar muscle, skin, fat, and TCL (Fig. 1c). Skin and fat were modeled as a single skin-fat tissue. Parts of the hamate and trapezium bones attached with skin-fat, muscle and TCL were modeled since the effects of bone strains are negligible relative to soft tissue deformation. Material properties of all components were listed in Table 1. Material properties of hamate and trapezium bones were assumed as isotropic, homo-

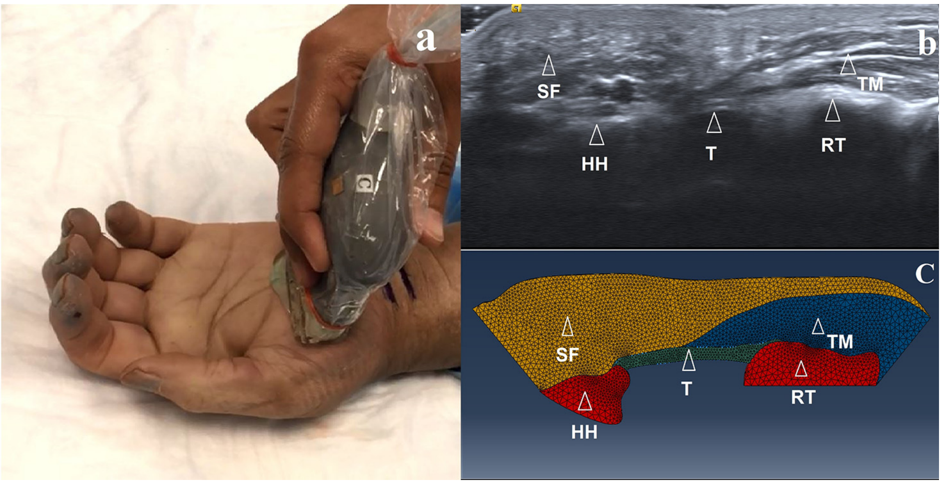

Fig. 1. FE model of the volar carpal tunnel based on ultrasound image. (a) Ultrasound image collection of the distal carpal tunnel; (b) The ultrasound image showing thenar muscles, skin-fat, TCL, hook of hamate and ridge of trapezium (c) FE model components including hamate bone, trapezium bone, thenar muscles, skin-fat and TCL. SF: skin-fat; HH: hook of hamate; T: TCL; RT: ridge of trapezium; TM: thenar muscles.

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