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Short communication

Development of a hyperelastic material model of subsynovial connective tissue using finite element modeling

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ABSTRACT

Carpal tunnel syndrome (CTS) is one of the most common disorders of the hand. Assessment of carpal tunnel tissue mechanical behavior, especially that of the subsynovial connective tissue (SSCT), is important to better understand the mechanisms of CTS. The aim of this study was to develop a hyperelastic material model of human SSCT using mechanical test data and finite element modeling (FEM). Experimental shear test data of SSCT from 7 normal subjects and 7 CTS patients collected in a prior study was used to define material response. Hyperelastic coefficients (μ and α) from the first-order Ogden material property definition were iteratively solved using specimen-specific FEM models simulating the mechanical test conditions. A typical Ogden hyperelastic response for the normal and CTS SSCT was characterized by doing the same with data from all samples averaged together. The mean Ogden coefficients (μ/α) for the normal cadaver and CTS patient SSCT were 1.25×10^{-5} MPa/4.51 and 1.99×10^{-6} MPa/10.6, respectively when evaluating coefficients for individual specimens. The Ogden coefficients for the typical (averaged data) model for normal cadaver and CTS patient SSCT were 1.63×10^{-5} MPa/3.93 and 5.00×10^{-7} MPa/9.55, respectively. Assessment of SSCT mechanical response with a hyperelastic material model demonstrated significant differences between patient and normal cadaver. The refined assessment of these differences with this model may be important for future model development and in understanding clinical presentation of CTS.

1. Introduction

Carpal tunnel syndrome (CTS) is a common hand disease, with incidence reported to be 2–4% in the adult population (Atroshi et al., 1999; Dekrom et al., 1992; Papanicolaou et al., 2001) and an estimated lifetime risk of 10% (Stevens et al., 1988). Key clinical features are high carpal tunnel pressure and fibrosis of the subsynovial connective tissu (Amadio, 1985, 2001; English et al., 1995; Ettema et al., 2004, 2008; Hadler, 1993; Latko et al., 1999; Mackinnon and Novak, 1997; Masear et al., 1986; Szabo, 1998). Understanding mechanical behavior of carpal tunnel tissues is important to fully understanding the mechanisms of CTS. Characterization of the SSCT stiffness is particularly important, as it surrounds tendons and median nerve in the carpal tunnel and influences the relative kinematic behavior between them. In previous studies, mechanical interactions between tendons, median nerve and SSCT were evaluated in normal and CTS tissues of both humans and rabbits (Vanhees et al., 2013, 2012; Yamaguchi et al., 2008; Yoshii et al., 2009a, 2008). SSCT behavior has been evaluated in both an in situ cadaver model (Filius et al., 2014; Vanhees et al., 2012) and through direct mechanical characterization of isolated tissue samples (Osamura et al., 2007). Osamura et al. defined the overall mechanical response with linear-elastic material properties; however the data curves appear to be non-linear with a strain-dependent response. The aim of this study was to develop an isotropic, hyperelastic material model based on experimental shear testing of harvested human SSCT (both normal and CTS) using a finite element modeling (FEM) approach and to determine if parameters differed between normal and CTS samples.

2. Materials and methods

The isotropic, hyperelastic SSCT material models were developed using mechanical test data acquired in a previous study (Osamura et al., 2007). Briefly, SSCT samples, 7 normal subjects and 7 CTS patients, were harvested from 5 fresh frozen cadavers (with no documented history of CTS) and from 7 wrists of seven adult idiopathic CTS patients undergoing open carpal tunnel release surgery. Samples were trimmed to 3 mm × 5 mm; subjected to thickness measurements; adhered to plastic plates and subjected to shear displacement at a constant rate of 1 mm/s until failure while measuring resistance force.

Three-dimensional, specimen-specific FEMs were constructed corresponding to the geometry of each individual test specimen from the above study using ABAQUS ver. 6.9 (Simulia, Providence, RI, USA) (Fig. 1). SSCT samples were modeled as rectangular prisms, 3 mm × 5 mm × T, where T is the thickness of each individual

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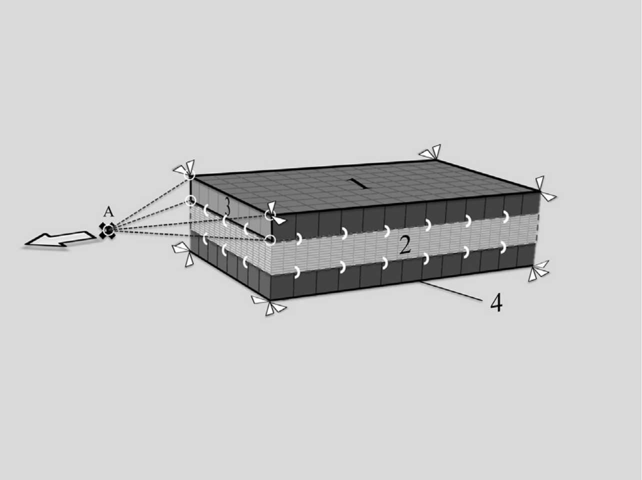

Fig. 1. Three-dimensional, specimen-specific FEA. Point A is a reference node for observing reaction force, triangles indicate direction of constraints and surfaces to which they were applied, semicircles show the location of tied nodes, and full circles indicate rigid body element. © 2015 Mayo Clinic. All Rights Reserved.

specimen. Plates were also modeled as rectangular prisms, 3 mm × 5 mm × 0.4 mm, positioned on the superior and inferior sides of the SSCT block. The model was meshed with linear hexagonal hybrid elements (C3C8RH) with dimensions of 0.2 mm × 0.2 mm × 0.04 mm for the SSCT and cube shaped elements, 0.4 mm on a side, for the plates.

Boundary conditions were applied to simulate the experimental test conditions. Elements at the SSCT/plate interfaces were tied (Fig. 1 semicircle). The top of the superior plate (Fig. 1, surface 1) was constrained to prevent motion in the superior–inferior direction and the medial–lateral direction as well as to prevent all rotations. Additionally, displacements at the rear wall of the SSCT (Fig. 1, surface 2) were confined to the transverse plane to stabilize the material behavior in the model. A reference node (Fig. 1, point A) for observing reaction forces was created at a point 2.0 mm offset from Surface 3 of the superior plate; the node was connected to Surface 3 by rigid body elements. The bottom of the inferior plate (Fig. 1, surface 4) was encastred. A longitudinal displacement (Fig. 1, arrow) was applied to the reference node at ramped displacement increments of 0.05 mm (for cadaver specimens) or 0.1 mm (for patient specimens) up to displacements of either 5 mm or 10 mm, as judged from experimental data of Osamura et al.

Plates were assigned a linear elastic material having a Young's modulus of 1000 MPa and Poisson's ratio of 0.4. The first-order Ogden hyperelastic constitutive model was used to model the SSCT. The strain energy, W, in this constitutive model is a function of deviatoric principal stretches (λ_n):

$$W(\lambda_1,\lambda_2,\lambda_3)=\mu/\alpha^2\left(\lambda_1^\alpha+\lambda_2^\alpha+\lambda_3^\alpha-3\right)$$

The coefficients μ and α predominately reflect the low-strain and high-strain stress–strain relationships, respectively (Main et al., 2011).

For each SSCT specimen modeled, initial isotropic, hyperelastic model parameters μ and α were generated from experimental stress–strain data using material calculation module of ABAQUS. Parameters were varied iteratively from this starting point until the coefficient of determination, R^2, calculated using a custom Matlab program (Math Works In., Natick, MA), became greater than 0.95.

Once hyperelastic parameters had been determined for each specimen, means of the coefficients μ and α were compared between normal cadaver and patient groups using the unpaired Student's *t* test. *P*-values of 0.05 or less were considered significant.

To better understand the role of each of the coefficients in the mechanical response of the material model, parametric analyses of nine new models were performed, each shearing a piece of normal SSCT tissue having the average cadaver thickness using different combinations of μ and α. The parameters were modified to cover observed combinations of each parameter assuming the minimum, mean, and maximum values that had previously been determined. Gross observations of the effective shear stress strain curve as affected by different parameters were described. Effective stress was defined as the applied load divided by the specimen cross-sectional area, while effective shear strain was defined as the angular deformation of the SSCT block.

3. Results

Of the 10 data sets generated in the study by Osamura et al., only 7 cadaver specimens (4 male, 3 female) and 7 patient specimens (2 male, 5 female) were acceptable for use in this study. The mean, standard deviation (SD) and range for donor ages of the subset were 82.0, 1.83 and 78–83 years and 45.4, 16.0 and 24–71 years in the normal cadaver and CTS patient groups, respectively. The mean, SD and range of SSCT thickness were 0.46, 0.11 and 0.33–0.63 mm and 1.70, 0.35 and 1.17–2.17 mm in the normal cadaver and CTS patient groups, respectively.

The FEM predicted force–displacement response was, generally, quite similar to experimental data for the normal cadaver group (Fig. 2). The mean (SD) Ogden coefficients, μ and α (Table 1), for the normal cadaver SSCT were 1.25×10^{-5} MPa (1.28×10^{-5}) and 4.51 (1.46), respectively. The same coefficients fit to the curve comprised of the average of all data were 1.63×10^{-5} MPa and 3.93.

In the CTS patient group (Fig. 3) (Table 2), one specimen (patient 1) yielded an extremely high value for μ, and since this was outside 4 SD's of the mean, it was considered to be an outlier. The mean (SD) μ and α for the CTS patient group were 1.99×10^{-6} MPa (3.95×10^{-6}) and 10.6 (2.28), respectively. The same coefficients fit to the curve comprised of the average of all data were 5.00×10^{-7} MPa and 9.55.

The mean value of μ was significantly lower in the CTS patient group compared to the normal cadaver group ($p=0.0399$). Conversely, the mean value of α was significantly higher in the CTS patient group compared to the normal cadaver group ($p=0.0001$).

Nine combinations of low, mean, and high values of μ and α for the control group, plus the average patient response for comparison, are shown in Figs. 4 and 5, with the former highlighting the material behavior for small strains and the latter showing the change in behavior at higher strains. At small strains (Fig. 4),

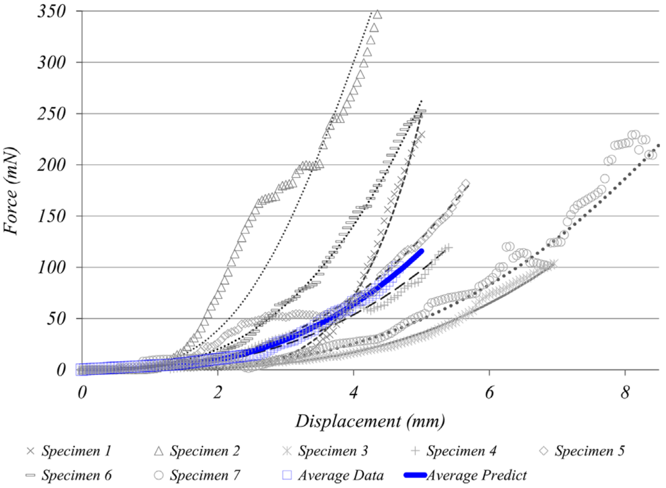

Fig. 2. Experimental and FEM-predicted force displacement response of the SSCT in normal cadaver tissue.

Table 1
The coefficients μ and α resulting in acceptable fit to each cadaver specimen and the average curve with other relevant parameters.

Specimen	Gender	Age	μ (MPa)	α	R^2	Thickness (mm)
1	f	83	1.00E−7	7.75	0.992	0.63
2	f	83	5.00E−5	4.4	0.957	0.38
3	f	83	3.00E−6	3.7	0.990	0.35
4	m	82	1.75E−5	3.95	0.969	0.51
5	m	82	2.00E−5	3.5	0.951	0.33
6	m	78	3.62E−5	4.085	0.997	0.51
7	m	83	6.00E−6	4.15	0.987	0.53
Average curve	–	–	1.63E−5	3.93	0.996	0.46
Average	–	82	1.25E−5	4.51	0.978	0.46
SD	–	1.83	1.28E−5	1.46	–	0.11