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Subject-specific finite element analysis to characterize the influence of geometry and material properties in Achilles tendon rupture

Vickie B. Shim [a,b,*], Justin W. Fernandez [a,c], Prasad B. Gamage [a], Camille Regnery [a,f], David W. Smith [d], Bruce S. Gardiner [d], David G. Lloyd [b,e], Thor F. Besier [a,c]

[a] Auckland Bioengineering Institute, University of Auckland, Auckland, New Zealand
[b] Centre for Musculoskeletal Research, Griffith Health Institute, Griffith University, Gold Coast, QLD, Australia
[c] Department of Engineering Science, University of Auckland, Auckland, New Zealand
[d] School of Computer Science and Software Engineering, University of Western Australia, Nedlands, Australia
[e] School of Sport Science, Exercise and Health, University of Western Australia, Nedlands, Australia
[f] ENSEIRB, MATMECH Bordeaux, France

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ABSTRACT

Achilles tendon injuries including rupture are one of the most frequent musculoskeletal injuries, but the mechanisms for these injuries are still not fully understood. Previous in vivo and experimental studies suggest that tendon rupture mainly occurs in the tendon mid-section and predominantly more in men than women due to reasons yet to be identified. Therefore we aimed to investigate possible mechanisms for tendon rupture using finite element (FE) analysis. Specifically, we have developed a framework for generating subject-specific FE models of human Achilles tendon. A total of ten 3D FE models of human Achilles tendon were generated. Subject-specific geometries were obtained using ultrasound images and a mesh morphing technique called Free Form Deformation. Tendon material properties were obtained by performing material optimization that compared and minimized difference in uniaxial tension experimental results with model predictions. Our results showed that both tendon geometry and material properties are highly subject-specific. This subject-specificity was also evident in our rupture predictions as the locations and loads of tendon ruptures were different in all specimens tested. A parametric study was performed to characterize the influence of geometries and material properties on tendon rupture. Our results showed that tendon rupture locations were dependent largely on geometry while rupture loads were more influenced by tendon material properties. Future work will investigate the role of microstructural properties of the tissue on tendon rupture and degeneration by using advanced material descriptions.

1. Introduction

Achilles tendinopathy, including tendon rupture, occur at a rate of about 250,000 per year in the US alone (Jarvinen et al., 2005; Pennisi, 2002). The mechanism of tendinopathy and rupture is complex and thought to be influenced by tendon geometry, material-strength, sex, disease and genetics. Achilles tendon ruptures are typically reported to occur at 2–6 cm above the insertion to the calcaneus bone, in a region that is hypovascular (Theobald et al., 2005). It is not understood why this region receives poor blood supply and is prone to rupture. Tendon rupture predominantly occurs in males with the reported ratios between men and women ranging between 2:1 (Lemm et al., 1992) and 12:1 (Bandak et al., 2001). Finite element (FE) analysis of the human Achilles tendon may provide insight into the possible mechanism of tendinopathy and tendon rupture as it can provide a standardized framework for systematic parametric and integrative analysis.

Previous computational models of the human Achilles tendon include 1-dimensional (1D) line elements to describe the tendon as a part of a foot model (Bandak et al., 2001; Bayod et al., 2012). Although such models are useful in predicting joint kinematics and kinetics, they cannot predict spatially varying 3-dimensional (3D) stresses and strains. These variables are most likely important in soft tissues like tendon that display large deformation and may have heterogeneous stress distribution patterns leading to regions of localized stress concentrations. To assess the possible reasons for the location of tendinopathy and rupture, and the aforementioned gender differences, 3D FE analyses may need to include subject-specific geometry and material properties.

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[*] Corresponding author at: Auckland Bioengineering Institute, 70 Symonds Street, Auckland, New Zealand. Tel.: +64 9 3737599x86932.
E-mail address: v.shim@auckland.ac.nz (V.B. Shim).

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Previous studies have investigated the relationships between the Achilles tendon geometry (e.g. length and cross-sectional area) and mechanical or structural properties of the tendon (Hess, 2010; Houghton et al., 2013; Jozsa et al., 1989; Kongsgaard et al., 2005). However, those studies were either in-vivo human or animal studies and could not comparatively analyze the influence of geometrical and/or material properties, and their inter-relationships, on tendon rupture. The aim of this study was to create subject-specific 3D FE models of the human Achilles tendon to evaluate how variation in geometry and material properties influence tendon mechanics. This included parameter optimization for a transversely isotropic hyperelastic material, which have been previously used to represent the material properties of different knee ligaments (Gardiner and Weiss, 2003; Quapp and Weiss, 1998; Weiss and Gardiner, 2001). Using these models, we simulated tendon rupture under uniaxial loading to investigate (i) the influence of the subject-specific geometry; and (ii) material properties on tendon 3D rupture patterns. We hypothesized that geometry and material properties of the tendon would influence the tendon's (i) rupture location, and (ii) rupture load.

2. Methods

2.1. Experimental data

Data from a previous experimental study were used (Wren et al., 2003). Briefly, in that study fresh-frozen human Achilles tendons from donors were imaged with high-frequency ultrasound. Specifically, the cross-sectional area of each tendon was measured at 2, 4 and 6 cm proximal to the tendon's insertion, which corresponds to the mid-section of the tendon. The ends of each specimen were gripped so that the grip-to-grip length was approximately 10 cm. Two types of mechanical testing (cyclic and creep testing) performed using a MTS machine (MTS, Eden Parairie, MN). Each tendon specimen had six markers along the centerline of the tendon and a CCD camera recorded movements of these markers during mechanical testing to enable material properties to be determined. Ten tendons (eight female and two male, average age 68 yr) from 18 specimens that underwent cyclic testing were selected for subject-specific FE modeling.

2.2. Generation of subject-specific FE model

Three cross-sectional ultrasound images of the ten selected tendons were segmented to describe subject-specific geometry. To create each FE tendon model, we used the computational framework developed as a part of the International Union of Physiological Society (IUPS) Physiome project (Fernandez et al., 2012; Hunter et al., 2002; Shim et al., 2011). A generic FE mesh of the human Achilles tendon was first developed using the Visible Human dataset. We used high order cubic Hermite elements, which preserve both the continuity of nodal values and their first derivatives. This type of element can describe smooth surfaces often found in biological structures such as the heart (Stevens et al., 2003), muscle (Oberhofer et al., 2010) and bone (Munro et al., 2013; Shim et al., 2012) with a lot fewer elements as each node has total 24 degrees of freedom. Therefore, our model has 32 elements and 72 nodes, which corresponds to 1728 degrees of freedom. This mesh density was chosen after convergence analysis. Free Form Deformation (FFD) (Fernandez et al., 2004) was then used to morph the generic tendon mesh to the segmented ultrasound images (Fig. 1). This involved morphing a host mesh to minimize the distance between identified landmark and target points. The embedded tendon mesh was then morphed to a subject-specific shape Fig. 2.

The tendon was represented as an incompressible, transversely isotropic hyperelastic material. It had a strain energy density function (Gardiner and Weiss, 2003) that modeled the tendon as a composite of ground substance matrix with embedded collagen fibers, i.e.

$$W = F_1(I_1) + F_2(\lambda) \tag{1}$$

where I_1 is the first invariant of the right Cauchy stretch tensor and λ is the stretch ratio along the local fibre direction. The function F_1 describes the behavior of the ground substance matrix and F_2 represents the behavior of collagen fibers. The ground substance was described with the neo-Hookian material model, i.e.

$$F_1 = \frac{C_1}{2}(I_1 - 3) \tag{2}$$

The strain energy of the collagen fibers was represented as a piecewise function that characterized their non-linear stress/strain behavior using the following (Weiss et al., 1996):

$$\begin{aligned} &\lambda\frac{\partial F_2}{\partial \lambda} = 0, \quad \text{for } \lambda \le 1, \\ &\lambda\frac{\partial F_2}{\partial \lambda} = C_3\left[e^{C_4(\lambda-1)} - 1\right], \quad \text{for } 1 \le \lambda \le \lambda^* \\ &\lambda\frac{\partial F_2}{\partial \lambda} = C_5\lambda + C_{6,} \quad \text{for } \lambda \ge \lambda^* \end{aligned} \tag{3}$$

where λ^* is the stretch value where the collagen fibers become uncrimped, while coefficients C_3, scales the exponential stress, C_4 represents the rate of collagen fibre loading, and C_5 modulus of the straightened collagen. To ensure a smooth transition between the 2nd and 3rd piecewise functions C_6 was determined using the following:

$$C_6 = C_3\left(\exp\left(C_4\left(\lambda^* - 1\right)\right) - 1\right) - C_5\lambda^* \tag{4}$$

2.3. Estimating the material properties

The values for the material coefficients were estimated using the cyclic experimental data. First, the value for C_5, the modulus of the straightened collagen, was obtained by taking the gradient of the linear region in the experimental stress/strain curve of the whole tendon. λ^* was kept constant at 1.055, the average value found from a previous study (Quapp and Weiss, 1998). The remaining material coefficients (C_1, C_3 and C_4) were estimated by performing material property optimization using a FE analysis to simulate the experiments. Boundary conditions simulated the experimental set up where the bottom nodes were fixed to represent the tendon clamp, while a force was uniaxially and equally applied to the top nodes to simulate the movement of the upper clamp during the experiments. The model was solved using finite elasticity mechanics in our open-source bioengineering software CMISS (www.cmiss.org) from which the predicted positions of the six markers from the experiment were computed. The root mean square (RMS) error between predicted and actual experimental marker positions was then computed.

The optimal material parameters were estimated by finding the minimum RMS marker position error via the non-linear least-squares *lsqnonlin* algorithm in Matlab's Optimization Toolbox (Matlab Version 2009b, The MathWorks, USA). The *lsqnonlin* algorithm used has been previously detailed (Babarenda Gamage et al., 2011). For each specimen, 5 different randomly generated initial parameter guesses were tested to ensure global minimums were found, which was the case.