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A damage model for the percutaneous triple hemisection technique for tendo-achilles lengthening

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A R T I C L E I N F O

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A B S T R A C T

A full understanding of the mechanisms of action in the percutaneous triple hemisection technique for tendo-achilles lengthening has yet to be acquired and therefore, an accurate prediction of the amount of lengthening that occurs is difficult to make. The purpose of this research was to develop a phenomenological damage model that utilizes both matrix and fiber damage and replicates the observed behavior of the tendon tissue during the lengthening process. Matrix damage was triggered and evolved relative to shear strain and the fiber damage was triggered and evolved relative to fiber stretch. Three examples are given to show the effectiveness of the model. Implementation of the damage model provides a tool for studying this common procedure, and may allow for numerical investigation of alternative surgical approaches that could reduce the incidence rates of severe over-lengthening.

1. Introduction

Although the percutaneous triple hemisection technique for tendo-achilles lengthening has been used for nearly 100 years (Hatt and Lamphier, 1947), the amount of tendon lengthening that occurs during the procedure remains difficult to predict. Many studies have shown the procedure to be relatively safe and effective (Costa et al., 2006; Hoffman and Nunley, 2006; Lee and Ko, 2005; Piriou et al., 2000; Redfern and Thordarson, 2008; Stauff et al., 2011). However, these studies also suggest that over-lengthening, or even full rupture of the tendon may occur, drastically reducing the patient's ability to walk. Therefore, accurate prediction of lengthening, as well as an enhanced understanding of the mechanisms of action in this procedure remain important topics to understand.

The difficulty in predicting lengthening is inherent in the procedure itself. It is performed by making three offset percutaneous cuts from the edge of the tendon to the approximate center of the tendon, followed by pulling the foot in dorsiflexion (Haro III and DiDomenico, 2007). When enough force is applied to the incised tendon, gaps are created at the locations of the incisions as the fibered sections slide relative to each other while being held together by a weakened extracellular matrix. Cadaver studies have shown that variations in the incisions made during the procedure drastically affect the overall amount of lengthening that occurs in the tendon (Hoefnagels et al., 2007). In some cases, the offset cuts are not sufficiently long to sever all of the connecting fibers, and those fibers must also weaken before any sliding takes place. Fig. 1 illustrates the lengthening process. Full rupture can occur if the matrix material becomes too weak to hold the sections of the tendon together. Since the biomechanics of the procedure are still unclear, mechanical results remain difficult to predict.

Because the weakened matrix material is responsible for holding the tendon pieces together, modeling this material behavior is important for predicting the success of the procedure. The behavior of weakened soft tissue for various other conditions, for both the matrix and fiber response, has been described through previously developed models that predict the behavior on a macroscopic scale (Calvo et al., 2007; Ehret and Itskov, 2009; Natali et al., 2005). Many of the models were developed using a non-linear continuum damage mechanics framework (Lemaitre, 1985) with the ability to describe irreversible effects (Simo, 1987; Simo and Ju, 1987a, b). The purpose of this research was to develop a non-linear continuum damage mechanics model that describes the specific matrix and fiber damage that occurs during the percutaneous tendon lengthening procedure. Application of this model may help to better understand and predict the amount of lengthening that occurs during the procedure.

2. Description of the damage model

To the authors' knowledge, a damage model has never been applied to evaluate triple hemisection tendon lengthening. Our

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approach mimics that employed by others in modeling damage in fibered soft tissues (Calvo et al., 2007; Ehret and Itskov, 2009; Natali et al., 2005), with the significant change of utilizing a shear strain driven damage criteria. This section contains a summary of the specific damage model that was used for this research.

The constitutive behavior of tendons is commonly decomposed into contributions from the collagen fibers and the extracellular matrix (Weiss and Gardiner, 2001). The free energy (strain energy) equation for the constitutive model chosen for this research can thus be represented by the decoupled form

$$\Psi = \overline{\Psi}_0^m(\bar{I}_1,\bar{I}_2)+\overline{\Psi}_0^f(\bar{\lambda})+\Psi_{vol}(J) \quad (1)$$

where Ψ_{vol} represents the dilatational strain energy and $\overline{\Psi}_0^m$ and $\overline{\Psi}_0^f$ represent the strain energies for the matrix and the fibers respectively. For the matrix and the fibers, the subscripts are used to denote that the material is undamaged. Thus, the complete strain energy Ψ, represents a transversely isotropic, incompressible material. $\bar{I}_1$ and $\bar{I}_2$ are the deviatoric invariants of the right deformation tensor, and $\bar{\lambda}$ is the deviatoric local fiber stretch. The dilational strain energy was defined as

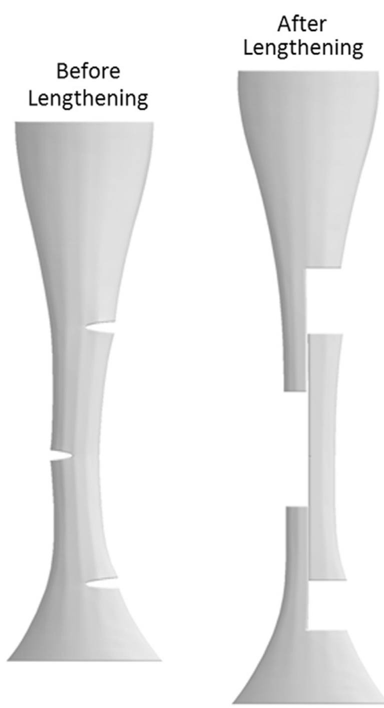

Fig. 1. Illustration of the percutaneous triple hemisection tendo-achilles lengthening process. The procedure is performed by making three offset percutaneous cuts which result in the creation of gaps at the locations of the incisions.

$$\Psi_{vol}(J)=\frac{K}{2}\ln(J)^2, \quad (2)$$

where K is the bulk modulus and J is the volume ratio. The strain energy for the matrix was represented by a Mooney–Rivlin material model where

$$\overline{\Psi}_0^m=\frac{C_1}{2}(\bar{I}_1-3)+\frac{C_2}{2}(\bar{I}_2-3). \quad (3)$$

The fiber strain energy $\overline{\Psi}_0^f$ was described in previous published research (Weiss et al., 1996) and is formulated using the following strain energy derivatives:

$$\bar{\lambda}\frac{\partial\overline{\Psi}_0^f}{\partial\lambda}=0, \quad \bar{\lambda}\le 1 \quad (4)$$

$$\bar{\lambda}\frac{\partial\overline{\Psi}_0^f}{\partial\lambda}=C_3\left(\exp\left(C_4(\bar{\lambda}-1)\right)-1\right), \quad 1<\bar{\lambda}<\lambda^* \quad (5)$$

$$\bar{\lambda}\frac{\partial\overline{\Psi}_0^f}{\partial\lambda}=C_5\,\bar{\lambda}+C_6, \quad \bar{\lambda}\ge\lambda^* \quad (6)$$

where C_6 is not an independent parameter, but instead represents the contribution of the fiber response prior to λ^*.

$$C_6=C_3\left(\exp\left(C_4(\lambda^*-1)\right)-1\right)- C_5\lambda^*. \quad (7)$$

Eq. (4) reflects the tissues inability to support a significant compressive load. Once in tension, the tissue initially experiences the stiffening response detailed in Eq. (5). When the stretch reaches λ^*, the constitutive response becomes linear as expressed in Eq. (6). The previously mentioned strain energy equations for the matrix and fiber materials can be used to produce the following second Piola–Kirchhoff stress for the undamaged material (Weiss et al., 1996) where $\bar{\mathbf{C}}$ is the deviatoric right Cauchy–Green tensor and the operator DEV is used to extract the deviatoric portion of the tensor in the reference configuration

$$\bar{\mathbf{S}}_0^m=J^{-2/3}\,\mathrm{DEV}\left[2\frac{\partial\overline{\Psi}_0^m}{\partial\bar{\mathbf{C}}}\right] \text{ and } \bar{\mathbf{S}}_0^f=J^{-2/3}\,\mathrm{DEV}\left[2\frac{\partial\overline{\Psi}_0^f}{\partial\bar{\mathbf{C}}}\right]. \quad (8)$$

The material damage was created by applying the damage factors, D_f and D_m, to the deviatoric portions of the stress (Simo, 1987) so that free energy becomes a function of the right Cauchy–Green strain tensor $\mathbf{C}$, and the factors D_f, and D_m. D_f, and D_m are normalized scalars from 0 to 1 representing the amount of phenomenological damage of the fibers and matrix respectively. This process must satisfy the Clausius–Duhem inequality such that

$$\dot{\Psi}-\tfrac{1}{2}\,\mathbf{S}:\dot{\mathbf{C}}\le 0 \quad (9)$$

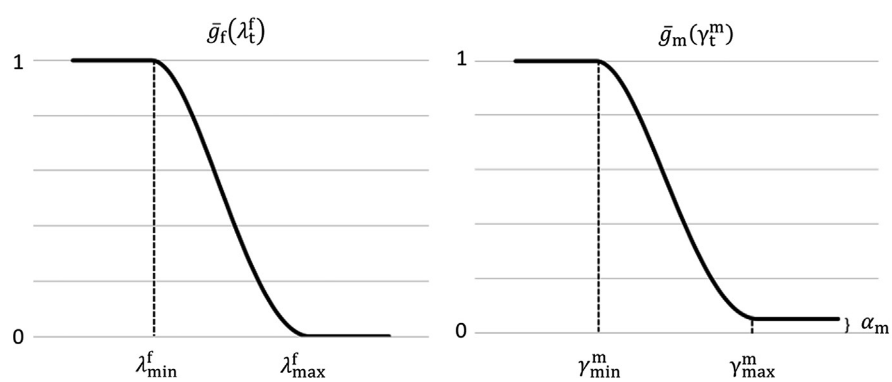

Fig. 2. Representation of the damage evolution functionals. The functionals have the value of one until the reach the minimum damage parameters where they will gradually decrease until they reach the maximum damage parameters.