Simulation of Percutaneous Achilles Tendon Lengthening Surgery Using A Finite Element Damage Model

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Introduction: Although the percutaneous triple hemisection technique has been used for nearly 100 years to lengthen the Achilles tendon [1], the amount of lengthening that occurs during this procedure is still difficult to predict. If the lengthening is not accurate, patients may lose their ability to walk. This procedure 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 [2]. Lengthening occurs when enough force is applied to the tendon to cause the cuts to spread apart and become gaps. During this process, sections of the tendon slide relative to each other but remain connected by a weakened matrix material. Over-lengthening occurs when that material becomes too weak to hold the sections of the tendon together. Cadaver studies have shown that variations in the percentage of the width of the tendons cut during the lengthening procedure drastically affect the overall amount of lengthening that occurs in the tendon [3]. Although these effects have been observed for many years, the biomechanics of this procedure that control the amount of lengthening are still unclear. The purpose of the research is to develop a nonlinear finite element damage model for use in predicting the biomechanical behavior of the percutaneous tendon lengthening procedure.

Methods: Finite element modeling is useful in predicting the normal (undamaged) mechanical response of tendons. When a damage model is added to the material formulation of the finite element analysis, it is then able to predict the behavior of the tendon once it has been weakened (damaged) due to overstraining. The damage model developed for this research was adapted from a previously published uncoupled directional damage model for fibred biological soft tissues [4]. In the present research, when the finite elements of the model reach prescribed levels of strain, the material response becomes less stiff and continues to weaken as the strain increases. Experimental testing was developed to validate the model and determine the parameters necessary for predicting the sliding behavior of tendons. 12 samples of freshly dissected porcine Achilles tendon were cut to a uniform thickness of 0.5 mm using a cryotome, and were approximately 1 cm by 0.5 cm. Two cuts on opposite sides were made in the sample from the edge of the sample to approximately the center of the sample. Graphite flakes were applied to the sample for strain tracking. Tension was applied to the samples, inducing a dramatic change in configuration (and damage to the matrix component of the tendon), representative of that exhibited during percutaneous tendon lengthening (Figure 1). Force and displacement data was recorded.

Results: The force and displacement data were analyzed against the measured strain to obtain the model parameters that were able to accurately predict force, displacement, and the amount of tissue sliding. Comparisons of tissue sliding between testing samples and the finite element model are shown in Figure 1.

The overall behavior of the damage model was qualitatively validated by finite element modeling of the percutaneous tendon lengthening surgical procedure in the human Achilles tendon. The damage parameters obtained from the porcine Achilles tendon were coupled with undamaged human Achilles tendon material properties and geometry obtain from published literature [5-7]. The deformation pattern and tendon lengthening that occurred in the model matched qualitative clinical observations of the procedure and is shown in Figure 2.

Discussion: A nonlinear finite element model was able to reproduce the tendon behavior that occurs during the percutaneous tendon lengthening procedure. In the finite element model, no actual sliding occurs between any of the elements, but instead the model produces a continuum behavior that is able to predict tendon lengthening, the force required to induce tendon lengthening, and material changes (damage) to the tendon matrix material. Thus, the model can be used to predict the likelihood of over-lengthening as a result of inaccurate scalpel cuts.

Significance: This work broadens our understanding of the biomechanics of percutaneous tendon lengthening. This understanding may lead to increased consistency in the success of this surgical procedure through accurate prediction of the amount of lengthening that occurs due to percutaneous incision dimension.

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Figure 1. Comparison of lengthening between porcine Achilles tendon testing samples and the finite element models used for verification.
Figure 2. Simulation of percutaneous Achilles tendon lengthening surgery.