A fibre-reinforced poroviscoelastic finite element model for the Achilles tendon

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Tendons connect muscles to bone and consist of a complex structure of almost parallel collagen fibres embedded in a hydrated matrix. The mechanical behaviour of tendons is viscoelastic and highly non-linear. The Achilles tendon is the largest tendon in the body and it is essential for walking and jumping. It is the most frequently ruptured tendon in humans and today there is no consensus on what is the best treatment. To be able to improve and develop suitable treatments for tendon injuries more knowledge in tendon mechanics is necessary. Computational models can increase the understanding of tendon mechanics and also be used to predict tendon rupture or the mechanical response in unknown loading situations. There are different models used for tendons today but most of them provide a mathematical description of the mechanical behaviour without any direct coupling to the physiological structure of tendons.

In this study, a structural fibre-reinforced poroviscoelastic finite element model is developed for the Achilles tendon, based on a model for articular cartilage. It is assumed that the collagen fibres, the non-fibrillar matrix and the fluid flow contribute to the total stress in the tendon and specific constitutive models are used for the different components. The fibres are modelled as non-linear viscoelastic one dimensional units, the surrounding matrix is modelled as a neo-Hookean material and the permeability is assumed to be strain-dependent. The model is curve fitted to experimental test data from rat Achilles tendons subjected to cyclic loading by optimizing nine material parameters. In total, the model is curve fitted to 21 specimens from two different data sets and two average tendons representing each set.

It was found that an exponential stress-strain relationship for the collagen fibres was necessary to capture the non-linear behaviour of the Achilles tendon. With this exponential formulation, very good curve fits were obtained for all specimens from both groups and for the average tendons. Statistical analyses show that the optimized material parameters from the two data sets are not significantly different. The proposed model can accurately simulate the Achilles tendons under cyclic loading and it identifies the collagen fibres to be the most important load bearing structural parts in tensile loading. This model also looks promising for predicting the general mechanical behaviour of the Achilles tendon under other similar loading conditions.

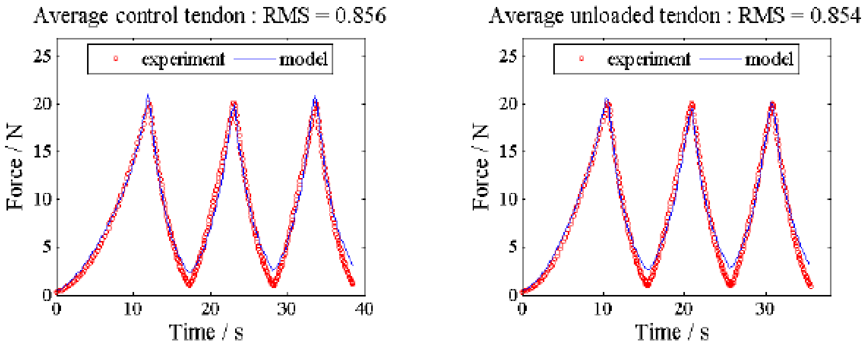

Figure: Curve fit of the average tendon from the control group (left, RMS=0.856) and unloaded group (right, RMS=0.854).