Finite element modeling of the human triceps surae aponeurosis based on force-diplacement data from in vivo motion tracking with Phase Contrast MRI

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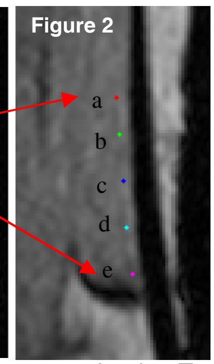
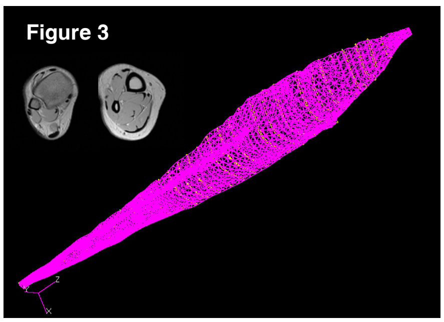
Introduction: A major obstacle in finite element modeling (FEM) of the musculoskeletal system is the lack of a detailed knowledge of the mechanical and structural properties of the tissues through carefully controlled mechanical testing. Such knowledge is not readily attained in biological tissues because the specimen to be tested is difficult to isolate for mechanical testing while preserving its normal physiological condition. Our objective was to use the empirically determined relationship between load and time response of the subject-specific human triceps surae aponeurosis, non-invasively acquired in vivo with the phase contrast imaging (PC-MRI) based technique described elsewhere[1, 2], in conjunction with the finite element modeling of the TSA to determine the material properties of some of the well-accepted constitutive models of hyperelastic materials. With the proper selection and fitting of a specific constitutive law, the robustness of the subsequent finite element model and constitutive law of TSA was validated by comparing the numerical results of the model with that of a second set of PC-MRI experimental data acquired at other spatial locations of the aponeurosis.



Materials and Methods: The time and displacement response of the distal aponeurosis at the specific location (Fig. 2-a) was experimentally obtained from two healthy males (age: 32 years, body mass: 81.7 kg and height: 165.1 cm) using the PC-MRI based technique[1, 2]. Three hyperelastic models (Neo-Hookean, Mooney-Rivlin, and Cubic) were qualitatively evaluated in terms of their ability to describe the hyperelastic response of tendinous tissues. The Cubic constitutive equation (its strain energy function defined below) was selected and least squares fitted to the experimental load-displacement data (Fig. 2-a) and the resulting constants of the energy function were calculated. The 3D geometry of the aponeurosis was generated by manually segmenting the aponeurosis boundaries from each of a stack of axial slices, 7 mm think, acquired with a T2 weighted TSE sequence across the entire length of the leg and with smoothing of the curves (Fig. 3). The FE mesh was generated in MSC.PATRAN. Subsequently, the FE simulation was performed in ABAQUS environment to predict the time response at 4 different anatomical locations along the TSA (Fig 2-b, c, d, e), which was compared to experimental data at locations different from the point where the materials constants were characterized in the aponeurosis from the same subjects as well as from two other subjects.

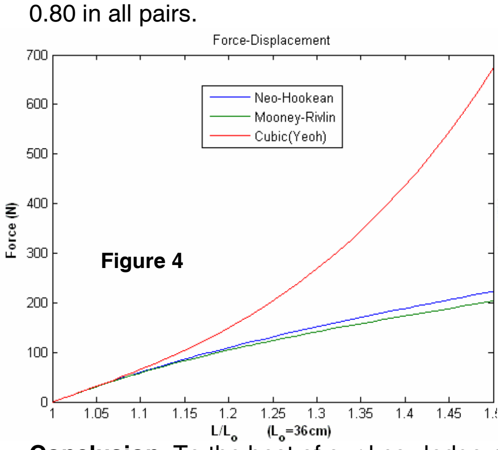


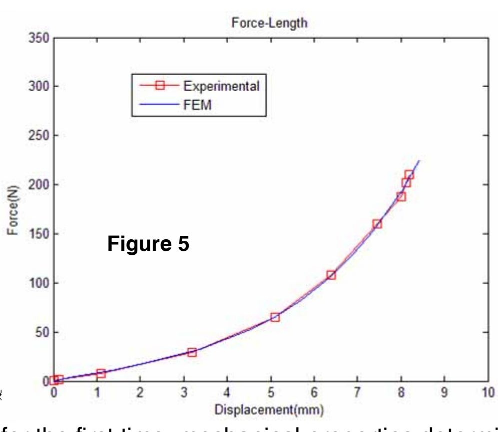
Results and Discussion: Force-displacement response of the three constitutive models, i.e. Neo-Hookean, Mooney-Rivlin, and Cubic are plotted in Fig. 4. The Cubic model's response best captures the stiffening characteristic behavior associated with soft tissues and thus was used as the constitutive law of our FE model. The characterized constants of its energy function are shown in the table below and its force-displacement response at Fig. 2-a was plotted together with that obtained in vivo using the PC-MRI based technique (Fig. 5).

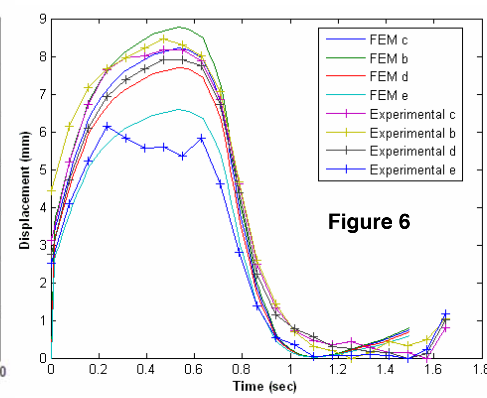
$$W = C_{10}\left(I_1-3\right)+C_{20}\left(I_1-3\right)^2+C_{30}\left(I_1-3\right)^3+\frac{K}{2}\left(J-1\right)^2$$

C_{10}	C_{20}	C_{30}	K
1 N/mm^2	8 N/mm^2	80 N/mm^2	2 x 104 N/mm^2

The predicted time response of TSA (Fig. 2-b, c, d, e) of the FE model was plotted together with that of the experiemnt (Fig. 6). FEM curves (b, c, d, e) and their respective experimental pairs trailed closely in time yielding the correlation coeffcient value greater than 0.80 in all pairs.







Conclusion: To the best of our knowledge, for the first time, mechanical properties determined in vivo by MRI was used to characterize constants of constitutive law in the finite element model and was verified to be in good agreement with independent set of experimental output at all tested anatomical locations. More complete FE model in the future based on the work presented here will help us to understand muscle-tendon system's normal function, predict changes due to alternations, and propose methods of artificial intervention.

References: 1. Finni T et al. J Appl Physiol 95: 829-837, 2003. 2. Sinha S et al. J Magn Reson Imaging 20: 1008-1019, 2004.