Prediction from Finite Element Modeling of Non-uniform, Region-dependent Strain of Muscle Fibers During Passive and Eccentric Rotation of the Ankle Confirmed by Phase Contrast MRI

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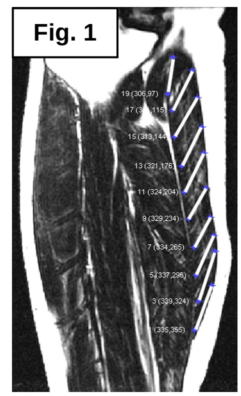
Introduction: Dynamic PC-MRI has provided significant understanding of the muscle-tendon system, particularly the strain behavior of the aponeuroses surrounding the triceps surae muscles[1,2]. We initially started our finite element (FE) modeling effort because of some unexpected observations in our PC-MRI data, i.e. regions of negative strain, somewhat contradictory to conventional understanding of the muscle mechanics. Our FE model has provided a clear rationale for this intuitively conflicting notion, underscoring the importance of muscle geometry and the interaction between passive and active elements. The model also suggests, again somewhat surprisingly, a non-uniform strain along individual muscle fibers, dependent on the location of the fibers within a muscle. To validate this therefore, we have investigated the *in vivo* distribution of strain along muscle fibers in different regions of the human medical gastrocnemius (MG) muscle using a PC-MRI technique and compared the theoretical output of the FE model with the empirical output of the PC-MRI data.

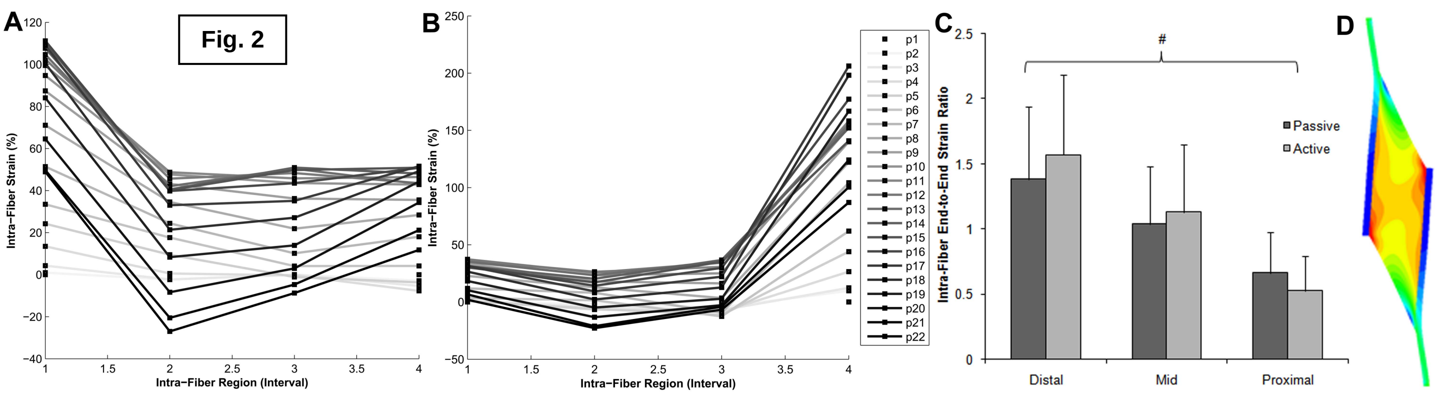
Methods: The FE model used a simple geometry for muscle-tendon complex, with the assumption that the materials composing the model maintain incompressibility. We also assumed that the material properties were homogeneous and the muscle fibers were straight and parallel to each other. Six healthy human subjects (height: 174.8 ± 4.1 cm, weight: 80.5 ± 12.9 kg, age: 31.5 ± 13.5 years) were studied after IRB approval under two modes of dynamic ankle rotation, i.e. passive and active eccentric contraction at 40% MVC. Prior to contraction-gated VE-PC-MRI acquisition (FOV: 16.5x30 cm, 141x256 matrix, Slice: 5 mm, TR/TE/FA: 16.5 ms/7.7 ms/20º, BW: ±15.6 kHz, VENC: 10 cm/s in 3 directions, VPS: 4, NEX: 2), water saturated TSE images were acquired on the same oblique sagittal slice (FOV: 18x30 cm, 154x256 matrix, Slice: 5 mm, TR/TE: 2500 ms/17.4 ms, BW: ±15.6 kHz, ETL: 7, NEX: 3) to maximize the contrast from fatty layers of connective tissue aligned in parallel with the fascicle arrangement in the MG. The muscle fiber ends were directly located along the length of the MG using this image. The two ends of each fiber and linearly interpolated points between the two were then tracked two-dimensionally using the PC-MRI data after one-to-one image registration. Intra-fiber strain was measured by calculating the distance variation between these points along each fiber during the dynamic ankle rotation[3]. For each fiber, the ratio of the strain at the left end (attached to the deep aponeurosis) to strain at the right end (attached to the superficial aponeurosis) was calculated and defined as the intra-fiber end-to-end strain ratio. This ratio was used to illustrate how one end of the fiber displaced relative to the other.

Fig. 1



Results & Discussion: Fig. 2A and B show the intra-fiber strain behavior of the most distal and proximal fibers in Fig. 1, respectively from a

Fig. 2



representative subject. There are 22 curves, corresponding to 22 contraction cycles. It can be seen that the left end of the fiber stretched more than the right end at the most distal location (Fig. 2A) and that the opposite was true at the most proximal location of the MG. This is also reflected in Fig. 2C, where the intra-fiber end-to-end ratio is greater than unity at the distal region and progressively decreases to less than unity proximally. This ratio was statistically different at the three regions[#] based on 2-way ANOVA. Fig. 2D is a FE model output showing the maximum principal contours of the muscle-tendon model under isometric contraction. The model shows that the proximal region of the superficial aponeurosis and the distal region of the deep aponeurosis experience the highest strain, which is consistent with the observations made from the PC-MRI data.

Conclusion: These findings confirm the model prediction that intra-fiber strain of muscle fibers is non-uniform and location dependent. It confirms and extends previous work showing interactions between contractile tissue and aponeurosis[4] by showing that strain heterogeneity also occurs in muscle without a central aponeurosis. High strains occur in regions of muscle which may be expected to experience high stress density.

References: **1.** Finni T et al. J Appl Physiol. 2003;95(2):829-37. **2.** Kinugasa R et al. J Appl Physiol. 2008;105(4):1312-20. **3.** Shin D et al. Proc. of 16th ISMRM, Toronto, 2008; pg 3671. **4.** Pappas GP et al. J Appl Physiol. 2002;92(6):2381-9.