ISB 2013 BRAZIL
XXIV CONGRESS OF THE INTERNATIONAL SOCIETY OF BIOMECHANICS
XV BRAZILIAN CONGRESS OF BIOMECHANICS

A DIFFUSION TENSOR IMAGING BASED MODEL OF MUSCLE MECHANICS

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SUMMARY

In this study we use Diffusion Tensor Imaging to create a 3D continuum model of the gastrocnemius muscle. In the first stage we have developed the idea using a rabbit model. DTI provides information about the 3D fibrous architecture used as part of the mechanics simulation and fiber-based constitutive law. A non-ferrous rig was designed to fit in an animal MRI which captured muscle shape and passive muscle force for 4 different dorsiflexion positions. Using an optimization routine within Matlab we determined the material parameters for the gastrocnemius (hind limb muscle) by matching muscle shape and force for each position. The DTI-based muscle was then used to perform mechanics simulations and was shown to produce more realistic shape change during deformation and when muscle contraction dynamics was included.

INTRODUCTION

Muscle shape and deformation is a product of boundary conditions, constitutive material response and most importantly the 3D fibrous architecture. The fiber organization influences the shape under contraction and also anisotropic muscle response. An improved understanding of fiber architecture will have benefits in determining moment arms in biomechanics, bone remodeling in orthopedics and even muscle shape in entertainment applications. Diffusion Tensor Imaging (DTI), a Magnetic Resonance Imaging (MRI) modality has been used to infer the direction of water diffusion, typically in cardiac and neural applications. Water moves most easily along the fibrous structures so DTI provides a map of the 3D fiber directions in muscle. Applications of DTI include the brain, spinal cord, kidney, and heart.

The rabbit animal model had become key to studying a number of pharmaceutical drugs, tendinopathies and graft implants. Motion analysis data and musculotendon force have also been measured. One model that is missing is an equivalent detailed 3D continuum model that can link to rigid body models and evaluate the spatially varying stress and strain. In this study we use DTI to track fiber orientation in a rabbit gastrocnemius muscle and develop a continuum description informed by optimized material properties from rabbit musculotendon extension experiments. The improved 3D contractile behaviors under isometric contraction conditions are evaluated.

METHODS

An adjustable non-ferrous mechanical rig to fit most sizes of rabbit was designed using a 3D printer (Figure 1). This was placed within the 4.7 Tesla animal MRI housed at the Centre for Advanced MRI (Auckland University). Following ethical approval a NZ white rabbit was euthanized by ear injection and then placed in the MRI for both a T1 weighted sequence (to obtain lower limb geometry) and 20 directions of a DTI sequence for fiber orientation. Using the bioengineering software CMISS (www.cmiss.org) we digitized and create finite element models of the lower limb. Secondly, using the Stejskal-Tanner relation [1] the diffusion tensor was computed for each pixel in the image volume. The tensor was decomposed into the 3 eigenvectors and the dominant eigenvector was then plotted at each pixel, representing the fiber direction.

Muscle is known to stiffen during rigor and then return to a passive state not to different from *in vivo*. Hence, muscle rigor was allowed to onset and then pass over a period of 70 hours. During this time we measured passive musculotendon force using a transducer fitted to the Achilles tendon. This was measured for 4 deformed positions. This process was repeated for 5 rabbits and the characteristic force for 1 rabbit is shown in Figure 2. We then optimized the constitutive materials properties (with a pole zero law) by using the known muscle shape (from MRI) and musculotendon force measured from the rig.

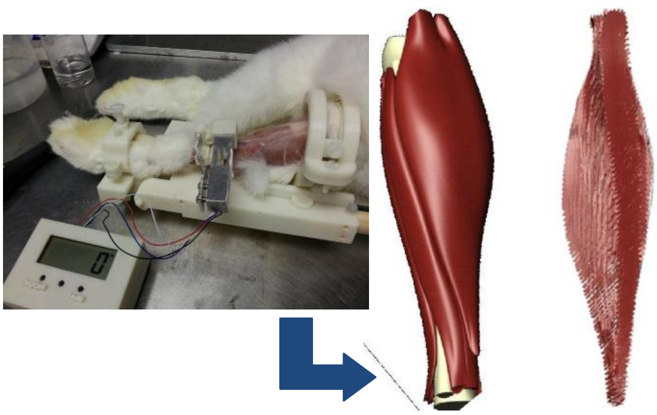

Figure 1: (Left) 3D printed MRI rabbit rig with force tranducer; (Middle) rabbit finite element model; and (Right) muscle fibers from DTI.

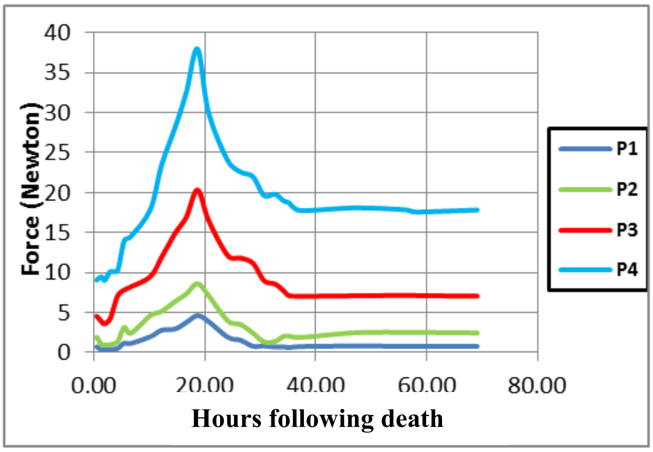

Figure 2: The graphs for one rabbit in four positions. P1 is the position when the foot angle is 15° dorsiflexion and P2 to P4 is 30°-60°.

RESULTS AND DISCUSSION

Figure 2 shows the typical response in passive muscle force following the onset and passing of rigor for increasing muscle length (P1 to P4). Following death the muscle stiffens over 20 hours and then reduces to a steady value after 40 hours. As this is a dynamic process the MRI and muscle force cannot be measured until after 40 hours. However, the graphs show the relationship between steady state and the *in vivo* force and how they may be related for different muscle length. The results are consistent with the work of Van et al [2].

Secondly, we performed a material parameter optimization using the Matlab Optimisation Toolbox [3] as shown in Figure 3 in order that the muscle model (in red) matched the deformed MRI shape (in gold) for the measured Achilles tendon force. This was performed until the RMS error was less than 2 mm and repeated for the 4 deformed positions.

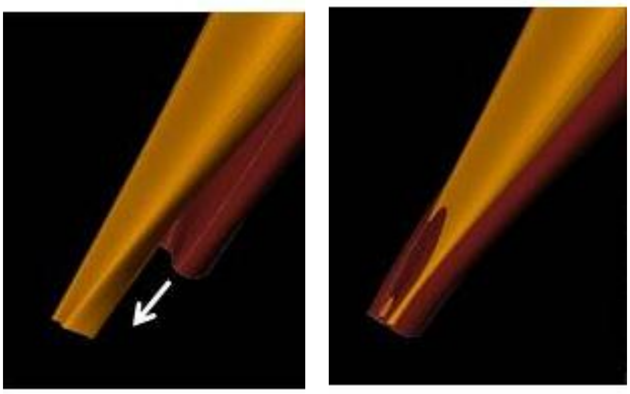

Figure 3: Optimization process matching muscle mechanics model (red) to MRI measured shape (in gold).

Finally, using the optimized muscle model we performed an isometric contractile mechanics simulation for the gastrocnemius based on simple Hill type contraction dynamics.

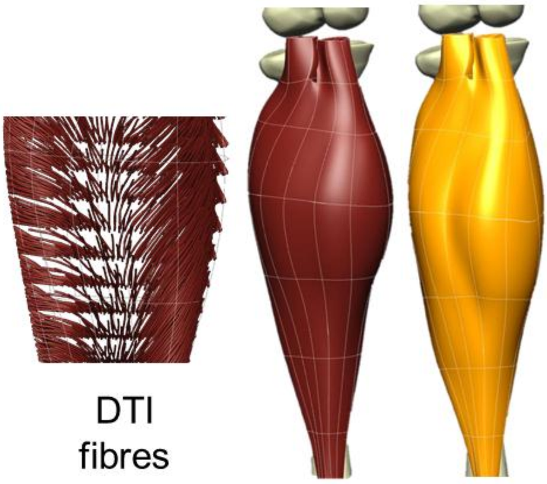

Figure 4: (Left) DTI based fiber field showing bi-pennation; (Middle) Isometric contraction when an isotropic uniform model is used; and (Right) when a DTI-based fiber model is used.

Figure 4 (left) shows the DTI fibers mapped as a continuum field using streamlines. The characteristic bi-pennation is observed. Figure 4 (middle) show the isometric contraction shape when no fibers are used representing an isotropic model. The muscle simply bulges in order to conserve muscle volume. When a transversely isotropic model is used informed by DTI fibers as shown in Figure 4 (right) then a crease between the lateral and medial heads is present. The medial head is also more distinct and the muscle bulges less, which is more anatomically correct.

CONCLUSIONS

This study has shown that the use of DTI improves muscle predictions of deformation, which in turn improves understanding of muscle function. Improved knowledge of muscle function has implications for moment arms in biomechanics, orthopedic interventions and computer visualization in medical education and virtual surgery.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Ministry for Science and Innovation, NZ for funding this study.

REFERENCES

1. Westin CF, et al., *Medical image analysis*, **6**(2):93-108, 2002.
2. Van Ee, et al., *Journal of biomechanical engineering*, **122**:9, 2000.
3. Babarenda, TP., et al., *International journal for numerical methods in biomedical engineering*, **27**(3):391-407, 2011.