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Mathematically Modeling the Effects of Electrically Stimulating Skeletal Muscle

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Abstract— **A framework for modeling the activation of skeletal muscle is presented for studying Functional Electrical Stimulation. A mathematical model of the cellular responses of skeletal muscle, created at AgResearch (Ruakura, New Zealand www.agresearch.co.nz), has been integrated with an anatomical, finite element model of the semitendinosus muscle, which was constructed from CT scans of the hind limb of a sheep. The tibial nerve was also constructed from digitized CT scans, and has been modeled using the Hodgkin Huxley neural model. The relevant cellular equations have been solved over these geometries. The results obtained, i.e speed of action potential propergation through the nerve and muscle, and the duration of twitch force, agree with published values.**

I. INTRODUCTION

One of the most physically destructive afflictions that can be suffered are those that result from impairment of human motor function. Functional Electrical Stimulation (FES) is an augmentation and rehabilitation technique that relies on the application of electrical stimulus to induce a tissue response [1]. There is currently a need for an accurate model of the electromechanical function of skeletal muscle, developed with FES in mind, to provide insight into the many facets of this procedure. Creating a geometrically customisable model of the neuromuscular pathways will allow investigation into;

1) The placement of electrodes
2) The strength of current required for various levels of activation at the electrode location
3) The stimulus protocol needed to elicit a specific movement
4) The stimulus train that corresponds best to the physiology of the muscles being activated (e.g. to reduce fatigue)

The smallest functional unit of skeletal muscle is the motor unit. A motor unit is made up of an α-motor neuron and all of the muscle fibers that it innervates. During normal physiological function, small motor units are recruited first and as more force is required larger motor units are recruited. The order of recruitment is fixed. During FES the order of recruitment is reversed. This is because larger motor units are innervated by larger motor neurons. These larger neurons are activated earlier when an external stimulus is applied [1].

The number of muscle fibers that are recruited during stimulation is dependant on the level of stimulation [1] [2]. In normal physiological situations this is controlled by the Central Nervous System (CNS). However when FES is applied, the magnitude of the stimulus current is the determining factor in the level of activation.

Modeling the neuromuscular pathways of skeletal muscle is an important step in developing a complete description of the function of skeletal muscle. In order to create such a model, the geometry of the muscles, bones and major nerves of the ovine hind limb were digitized, and finite element meshes fitted to this data. The sheep was selected for investigation as it is possible to measure the properties of the relevent tissues invasively. Specifically tendon forces and intramuscular pressure can be measured allowing the total muscle force to be determined. It is also possible to perform various stimulation protocols, replicating the effects of FES, and determine the muscle forces generated by these protocols.

II. METHODS

A. Creation of Muscle Model

The muscle model that is used in this research was created from digitized CT images of the ovine hind limb (see figure 1). A finite element surface mesh was fitted to the data cloud created from this digitisation using automatic fitting algorithms [3]. This surface mesh used cubic Hermite basis functions to capture its geometry. This surface mesh was then converted to a volume mesh with linear basis functions used to interpolate along the radial direction. One dimensional fibers were generated within this volume mesh following the geometry of the semitendinosus as a course representation of the individual fibers in the muscle.

A skeletal cell muscle model, created at AgResearch, was applied to these muscle fibres. This model is able to reproduce a number of cellular properties including the action potentials of the sarcolemma and T-tubule various internal and external ion concentrations, Ca^{2+} cycling from the Sarcoplasmic Reticulum to the contractile elements and the cycling of the actomyosin crossbridges. This model is also able to partially reproduce the fatigue response of skeletal muscle to stimulus trains of different frequencies. This is an important feature to have as fatigue is one of the limiting factors in the prolonged high intensity use of FES systems.

The tibialis nerve was also digitized from the same CT images as the semitendinosus. This data was fitted using ond dimensional linear elements. The Hodgkin and Huxley [4] cell nerve model was used to represent the membrane

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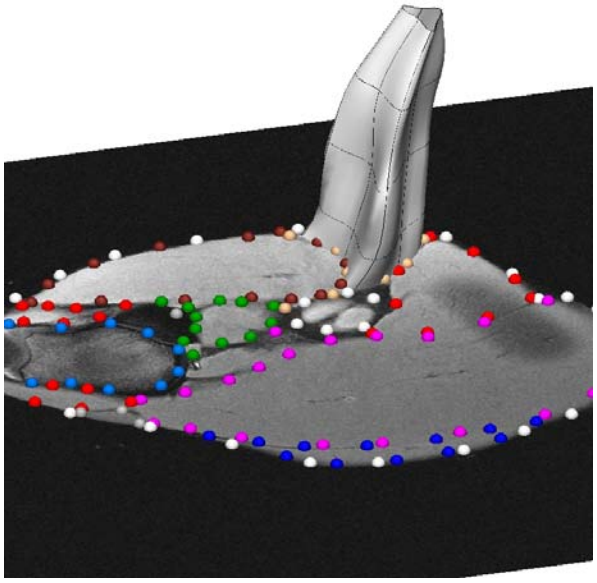


Fig. 1. The surface mesh of the semitendinosus with a CT image showing the digitized data points for the various muscles and bones within the segment

potential in the neural tissue. This combined model was solved using a mathematical modeling package developed and the Bioengineering Institute.

The semitendinosus was chosen as it is a muscle that is commonly used as an experimental muscle at AgResearch. It also has a relatively simple fiber direction which runs parallel with the direction of force generation [5].

Key Features of the Model

The semitendinosus is a fusiform muscle, i.e. it is divided into two halves by a tendinous inscription [5]. This model has this inscription dividing the muscle into two identically long halves. The electrical isolation of the individual fibers is achieved by modelling them as separate, one dimensional elements. The α-motor neurons innervate the two compartments of the muscle at their mid points and the motor endplate band is located at this midpoint.

B. Nerve Modeling

The connection between the digitized nerves and the muscle motor units of the semitendinosus are provided by an automatically generated nerve tree. This network allows for the action potentials, which are conducted along the major nerve, to be transmitted to, and activate the muscle fibers.

The nerve tree was created by generating bifurcations of the manually created offshoots from the tibialis nerve. In this way the tibialis was able to be directly linked with each simulated motor end plate in the tissue.

C. Activation Using the Nerve Model

To model the different levels of activation of the muscle, it is necessary to be able to activate some paths of the nerve model while leaving others inactive. The model demonstrated here does this by only generating the required number of neural innervation's and motor units for each individual stimulus level. This also allows for much easier visualisation of the output of the model. The connections between the large digitized nerve and the insertion point in the muscle are here modelled as linear. The connections between the artificially generated nerve branches and the muscle fibers are also modelled as linear axons. The examples show 100% activation and 50% activation of a limited number of muscle fibers (see below).

III. RESULTS

The finite element geometry of the tibialis and the semitendinosus can be seen in figure 2. An example of the output from the model can be seen in figures 3 and 4. To allow modelling of the effects of different levels of recruitment on the muscle, variable numbers of innervated muscle fibers are able to be generated. In the semitendinosus there are on average 712 motor units [6] containing arround 1000 muscle fibers. The results shown below are for 60 explicitly modeled muscle fibers (see figure 4).

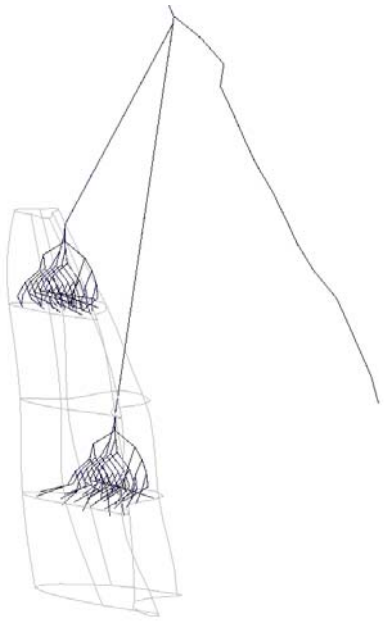
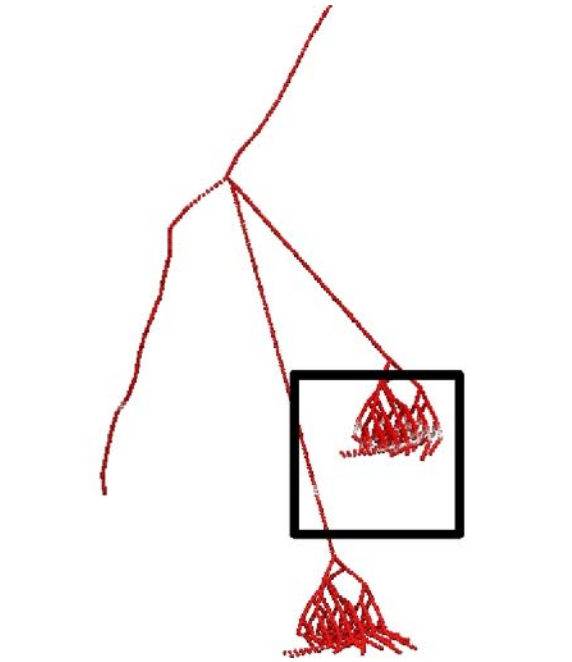
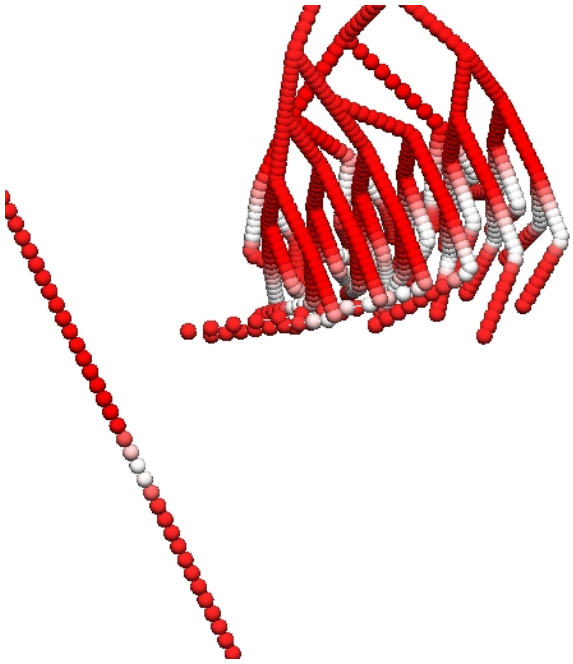


Fig. 2. The volume mesh of the semitendinosus muscle and the linear mesh of the tibial nerve from digitized data. Note the two branchs and the nerve trees that insert into the muscle are not from digitized data but generated at a later stage

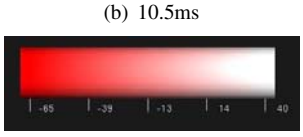
As can be seen, the activation of the nerve causes a corresponding activation of the fibers in the muscle. The speed of propagation of the signal along the nerve is much faster than the propagation of the signal along the muscle fibers. The speed of neural propagation is approximately 100 ms^{-1} which agrees with published values for α-motor neurons [7]. The speed of transmission in the muscle is approximately 2.5 ms^{-1}, which is close to the published speed for transmission of skeletal muscle action potentials (4 ms^{-1} [8]). The activation of the proximal half of the semitendinosus occurs earlier than in the distal half, however this time difference is only about 3 ms. The time difference between the initial activation of the proximal compartment



(a) 10.5ms

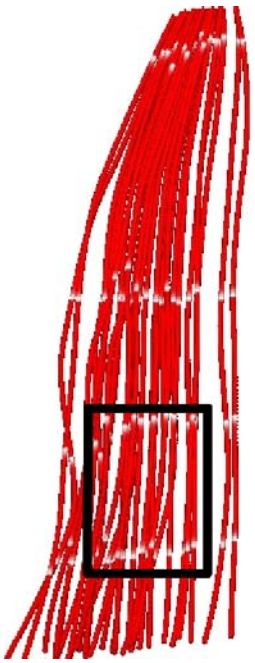


(b) 10.5ms

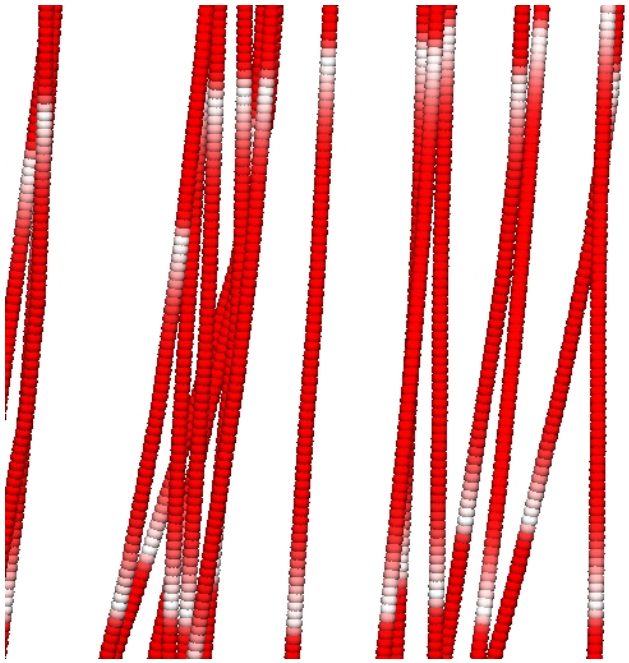


(c) Spectrum mV

Fig. 3. Electrical activation of the tibial nerve. The full nerve tree is shown in (a) and a magnified image of the nerve tree is shown in (b). The potential of the nerve is indicated in the spectrum shown in (c)



(a) 17ms



(b) 17ms

(c) Spectrum mV

Fig. 4. Electrical activation of the semitendinosus muscle fibres. 60 fibers are shown in (a) and a magnified section of the fibers are shown in (b) so that the electrical activation is visable. The potential of the muscle fibers is indicated in the spectrum shown in (c)

and the finish of propagation in the distal compartment is 11 ms. When compared to the time course of the twitch, during which eighty percent of the of the crossbridges are attached for almost 10 ms and over half of the crossbridges are attached for more than 30 ms (see figure 5) this difference in activation does not stop the muscle from contracting synchronously.

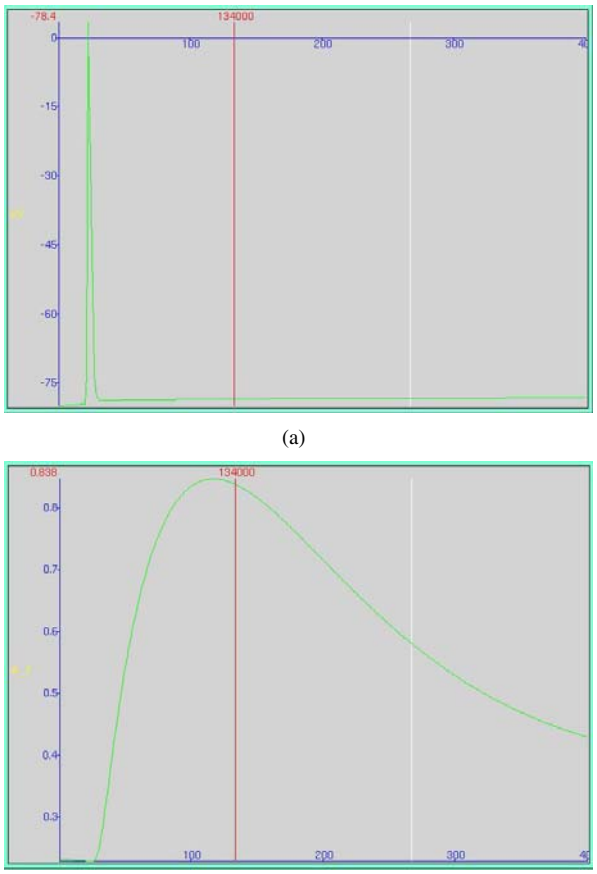


Fig. 5. Sarcolemmal action potential (mV) (a) and the proportion of attached crossbridges in the post powerstroke state (at any point in the tissue) (b). The scale of the x-axis is tenths of a millisecond.

IV. DISCUSSION

The results that were obtained from the neuromuscular model reflect the general physiology of skeletal muscle, i.e. fast conducting α-motor neurons, slower conducting muscle fibers with a delayed, long duration muscle force. The geometry of the semitendinosus-tibial nerve system has also been accurately represented. The output from this model (specifically the number of attached crossbridge in the pre and post powerstroke phase of their cycle) will be used as input into a finite elasticity mechanics model of the muscle. Using this mechanics model, force and displacement values will be able to be produced which will be able to be validated against experimental data obtained from AgResearch.

Further refinements to the cellular and muscle models are required before validation can be attempted. These refinements will include.

1) Use of physiological conductivities for sheep skeletal muscle fibers so that the speed of propagation through the muscle lies within normal bounds
2) A more anatomically accurate description of the tendinous inscription within the semitendinosus
3) The creation of intrafascicularly terminating muscle fibers and a distribution of endplates to activate these fibers to better represent the anatomy of the sheep

Once the full muscle model has been produced further modeling work needs to be directed at the requirements and effects of stimulating nerves cutaneously. Being able to link this information with the full muscle model (partially presented here) will be a powerful predictive tool for the analysis and production of FES systems. It will also allow for the optimisation of location of electrodes and refinement of stimulation protocols for existing FES systems. This step obviously requires a transition from the ovine anatomy and physiology to that of the human. This will be relatively straight forward, as the framework that is being produced is being created with this objective in mind. The cellular model is a general mammalian model which is easily transferable and the tools that have been produced to allow for the creation of the muscle model are directly applicable to the production of human muscle models.

REFERENCES

[1] D. Popovic and T. Sinkjaer, *Control of Movement for the Physically Disabled*. Cener for Sensory-Motor Interaction Aalbourg University: Academic Mind, 11000 Belgrade, Yugoslavia, 2nd edition ed., 2003.

[2] E. Henneman, G. Somjen, and D. Carpenter, "Functional significance of cell size in spinal motoneurons," *Journal of Neurophysiology*, vol. 28, pp. 560–580, 1965.

[3] C. Bradley, A. Pullan, and P. Hunter, "Geometric modeling of the human torso using cubic hermite elements," *Annuals of Biomedical Engineering*, 1997.

[4] A. Hodgkin and A. Huxley, "A quantitative description of membrane current and is application to conduction and excitation in nerve," *Journal of Physiology*, vol. 117, pp. 500–544, 1952.

[5] A. Paul, "Muscle length affects the architecture and pattern of innervation differently in leg muscles of mouse, guinea pig, and rabbit compared to those of human and monkey muscles," *The Anatomical Record*, vol. 262, pp. 301–309, 2001.

[6] A. d. C. Hamilton, K. Jones, and D. Wolpert, "The scaling of motor noise with muscle strength and motor unit number in humans," *Experimental Brain Research*, 2004.

[7] G. Tortora and S. Grabowski, *Principles of Anatomy and Physiology*. John Wiley & Sons, Inc., 9th ed., 2000.

[8] A. Harris, M. Duxson, J. Butler, P. Hodges, J. Taylor, and S. Gandevia, "Muscle fiber and motor unit behaviour in the longest human skeletal muscle," *Journal of Neuroscience*, vol. 25, no. 37, pp. 8528–8533, 2005.