Modeling static force generation of rat hindlimb muscles by direct stimulation

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INTRODUCTION

Musculoskeletal models are generally created from the bottom up: researchers first measure various parameters of muscle function, then put these parameters into a structural model to predict muscle actions (Delp and Loan, 2000). Although these methods have clearly been greatly successful, it can be difficult to assess the validity of these models.

We describe here a complementary method of creating a musculoskeletal model from the top down: starting with measurements of the true actions of muscles, then building a model to account for these measurements (Loeb et al. 2000). Although the resulting model is structurally similar to that used in bottom up approaches, it is constrained to predict the true action of muscles. This method can potentially help inform traditional muscle modeling procedures, helping to improve the accuracy and utility of musculoskeletal models.

METHODS

We characterized the actions of individual hindlimb muscles in the rat by direct stimulation. The hip was immobilized by posts placed in the pelvis and the distal tibia attached to a 6 degree of freedom force transducer (ATI). Bipolar electrodes were implanted into the muscle at its motor point. Muscles were stimulated using trains of biphasic constant current pulses (70-100Hz, 0.2ms, 0.5-1s train duration). Insulation was placed as necessary to prevent current spread to adjacent muscles. The limb was fixed in a configuration, the muscle stimulated, and the evoked forces and moments recorded. This procedure was repeated for 10-12 configurations of the limb, characterizing the configuration dependence of the muscle. The response at each configuration was summarized as the peak evoked response and converted to joint torques using the measured limb Jacobian.

We then used this isometric data to fit a parametric model of static muscle actions. This model comprises the static component of standard lines-of-force models, consisting of an anatomical model of the muscle path and moment arm and a model of the force generating characteristics of the muscle. Although such models are commonly used, choosing a muscle path can often be difficult, especially for muscles with broad insertions or origins. Our approach provides a way to empirically determine the best approximation. We assumed that the muscle path was fully described by point insertion and origin. This model can be described by the following set of equations:

$$l = f(\theta \mid x_o, y_o, z_o c);$$
$$\tau = R(\theta)^T \cdot F_M\left(l \mid L_{opt}, F_{opt}\right)$$

where τ are the joint torques, θ are the joint angles, R is the moment arm of the muscle, l is the effective muscle length, and the function F_M characterizes the force generating properties of the muscle. The free parameters x_o, y_o and z_o specify the origin of the muscle, c is the insertion point of the muscle along the tibia, L_{opt} is the optimal muscle length, and F_{opt} is the force produced by the muscle at its optimal length. We approximated the active force length function as a simple Gaussian, with mean L_{opt}. We then fit the model parameters using the measured muscle force data. We chose initial parameters based on the known anatomy (Greene, 1963), then used optimization to update these parameters.

RESULTS

We started with a simple version of the model described above, characterizing the action of the muscle in the sagittal plane. The measured action of semitendinosus is shown in the open arrows of Figure 1. Note that the direction and magnitude of the force are systematically altered as a function of the limb configuration. We attempted to fit the parameters of the structural model described above. The resulting model is shown in Fig. 1 in the overlaid filled arrows. The force vector indicated with a circle at the base was not used for the model fit but represents a generalization prediction of the model. As can be seen in the figure, the paramaterized model fit does a very good job of characterizing the observed muscle action. Across muscles (n = 6) and rats (n = 6), we have found that these models were able to predict approximately 95% of the variance in the observed muscle action.

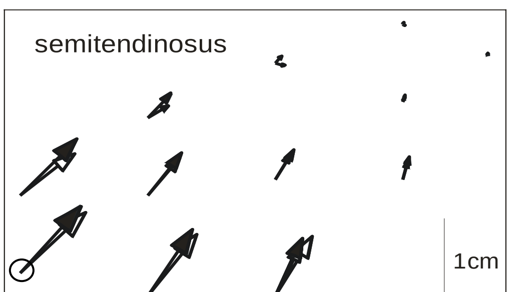

Fig 1 Results of parameterized model fits to force field data, showing the fit (filled arrows) to the force field from ST (indicated here with the open arrows).

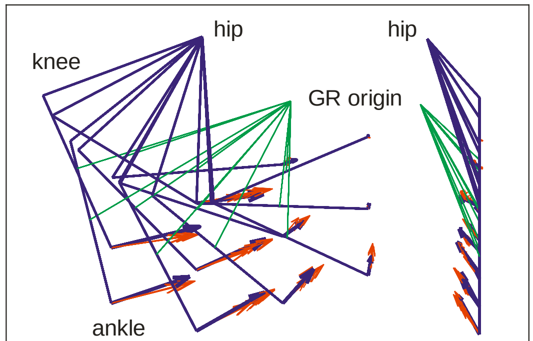

Fig 2 3D parameterized model fit. Blue lines show the limb, green shows the predicted muscle path. Red vectors are measured forces, blue vectors are predicted forces.

Figure 2 shows the extension of this approach to predict the full 6 dimensional action of gracilis (GR). In this case, the measurement of muscle action was repeated 8 times (red arrows). This data was then used to fit the model (blue arrows). Overlaid on the plots are the limb configurations and predicted muscle paths. As can be seen in the figure, the model did a good job of predicting the muscle action and the predicted anatomical path corresponds to the known anatomy of this muscle.

CONCLUSIONS

We have described an approach to muscle modeling based on directly measured muscle actions and demonstrated its utility. We are currently evaluating this approach in further detail, comparing the models created by this approach to those created by measuring muscle parameters directly. By combining information from the two approaches, we hope to continue to refine and improve our rat hindlimb model.

REFERENCES

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