IN VIVO PARAMETER ESTIMATION FOR THE HUXLEY CROSS-BRIDGE MODEL

[1,*] Alistair Vardy, [1]Erwin de Vlugt and [1]Frans van der Helm
[1]Biomechanical Engineering, Delft University of Technology, The Netherlands
[*]Contact: a.n.vardy@tudelft.nl

SUMMARY

The Huxley cross-bridge model is largely unused in musculoskeletal modeling despite its ability to accurately predict muscle stiffness properties and provide information related to muscle energy consumption. Using wrist perturbation experiments, we show that reliable model parameters estimates can be obtained and illustrate how model parameters depend on different biomechanical conditions. Furthermore, the model was formulated in such a way that it can be readily integrated with musculoskeletal models.

INTRODUCTION

Musculoskeletal models such as the Delft Shoulder and Elbow Model [1] aim to model the human musculoskeletal system as accurately as possible. Currently, these models use the ubiquitous Hill muscle model [2]. Although this model has computational advantages and many properties of muscle behavior are captured, the Hill model cannot account for the phenomenon of short-range-stiffness (SRS), and it does not afford insight into the muscle energy consumption.

SRS in particular is an important property of muscle that manifests during the first phase of muscle stretch and shortening, especially during ballistic movements. The Huxley muscle model [3] is based on the cross-bridge kinetics and is therefore physiologically more accurate than the Hill model. Moreover, SRS is an emergent property of this model and it provides direct insight into muscle energy consumption. Accurate estimates of stiffness properties and energy consumption are essential for musculoskeletal models, in particular for solving the load sharing problem and investigating neural control of movement.

At the moment, Huxley model parameters are unknown for different force levels and muscle stretch and contraction velocities in humans. This study is an attempt to estimate Huxley model parameters in vivo in humans during wrist perturbation experiments.

METHODS

Eight healthy subjects (age 25±4 years, 4 males) participated in the experiment. The right arm of the subject was fixated at the elbow and wrist (Figure 1). The wrist was perturbed 0.15 rad (both flexion and extension; only flexion data were analyzed) at 5 perturbation speeds (0.65, 1.30, 1.95, 2.60, and 3.25 rad/s) and for 3 initial loads (0.9, 1.5, and 2.1 Nm) yielding a total of 15 conditions. Each condition was repeated 3 times; initial torque level and perturbation velocity were counterbalanced.

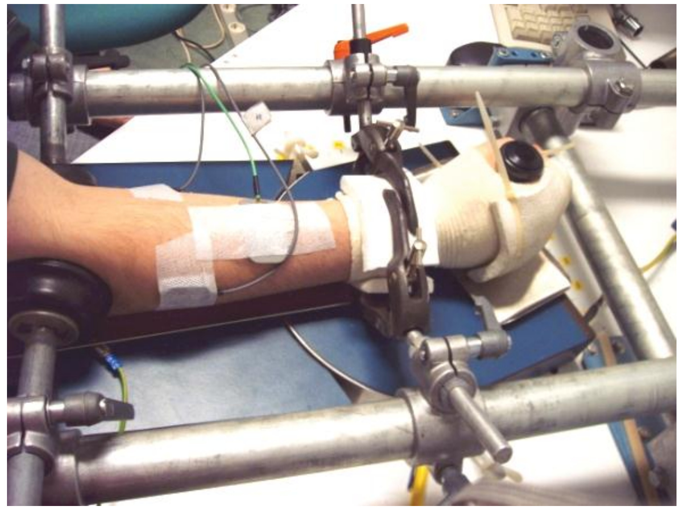

Figure 1: Experimental setup showing the elbow and wrist fixation and the wrist perturbator.

The two-stage Huxley muscle model with piecewise linear binding and unbinding rate functions was used [4] to described muscular contraction. The Huxley model is given by the following first order partial differential equation:

$$n_t - v(t)n_x = f(x) - [f(x) + g(x)]n$$

where $n(x,t)$ is the cross-bridge distribution at time t and bond-length x, v is the contraction velocity, and $f(x)$ and $g(x)$ are the binding and unbinding rate functions shown in Figure 2 and given by:

$$f(x) = \begin{cases} 0 & x < 0 \\ f_1\left(\frac{x}{h}\right) & 0 < x < h \\ 0 & x > h \end{cases}$$

$$g(x) = \begin{cases} g_2 & x < 0 \\ g_1\left(\frac{x}{h}\right) & 0 < x < h \\ g_1\left(\frac{x}{h}\right) + g_3\left(\frac{x}{h} - 1\right) & x > h \end{cases}$$

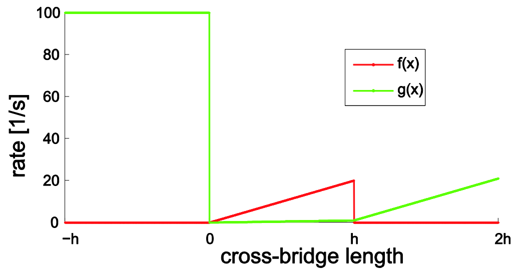

Figure 2: Binding and unbinding rate functions $f(x)$ and $g(x)$.

The Huxley model requires 5 parameters: the bond length h, indicating the distance at which a cross-bridge can no longer be formed, the binding rate parameter f_1, and three unbinding parameters g_1, g_2, and g_3. The parameter g_1 was taken equal to zero and g_2 was not used as it is not required when the muscle is stretched from stationary states. The wrist joint and tissue properties were modeled using a mass-spring-damper model.

Huxley model parameters were determined using nonlinear least square optimization where the parameters where optimized for each condition separately. Properties of the wrist joint and the hand tissue were assumed to be constant over conditions and their values were held equal in all conditions during the optimization.

RESULTS AND DISCUSSION

The Huxley cross-bridge model was implemented as a non-linear state space model. Relevant model parameters (bond-length h, binding rate parameter f_1, and decoupling rate parameter g_3) depended on both initial torque level as well as perturbation velocity (Figure 3).

Resulting predictions of wrist torque corresponded well with measured data (Variance Accounted For, VAF, of 95% and higher). Model fits are displayed in Figure 4.

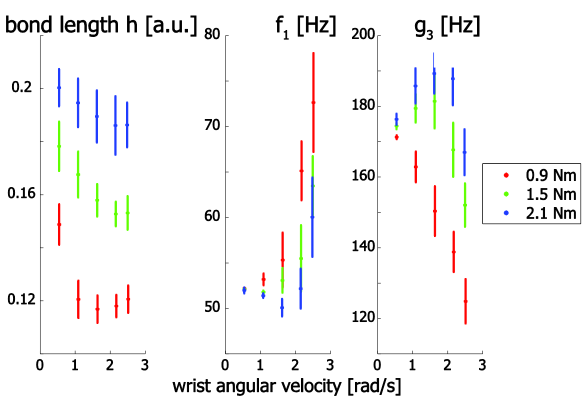

Figure 3: Estimates of relevant Huxley model parameters (h, f_1, and g_3) for each of the measured wrist velocity, grouped by initial torque level.

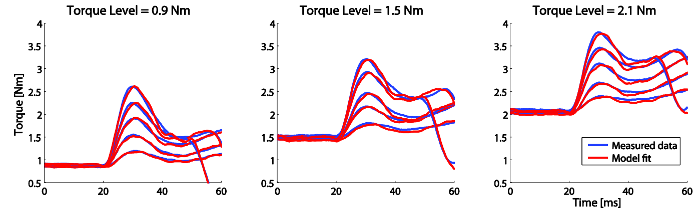

Figure 4: Model fits. All conditions showed parameter estimation with VAFs of at least 95% indicated an excellent model fit.

The Huxley model is based on microscopic properties which affords a physiological interpretation of muscle force development unlike the Hill muscle model. However, we found that the parameters depended on the state of the muscle (in line with [5]) which complicates this interpretation. As values of the parameters were unknown, the optimization was not constrained to a single set of parameters. Also, the model did not contain a tendon. Nonetheless, parameter estimates were consistent across participants indicating that parameters can be reliably estimated. In addition, preliminary results using an extended Huxley muscle tendon complex indicate that when only the bond length h is varied and rate parameters remain constant over conditions, good agreement between model predictions and experimental data can be found.

CONCLUSIONS

We conclude that the Huxley cross-bridge model is a valuable model which has advantages over the Hill muscle model despite being significantly more complex. We have shown that reliable Huxley parameter estimates can be obtained which agree across participants. Furthermore, the Huxley model provides more accurate descriptions of stiffness properties such as SRS, and affords direct estimates of energy consumption which can both be used in inverse-dynamical problems such as the load sharing problem. Finally, by formulating the model as a non-linear state space model, it can readily be applied to existing musculoskeletal models.

ACKNOWLEDGEMENTS

This work is part of the STIFF project which is funded by the 7th Framework Programme of the European Union (grant agreement No: 231576)

REFERENCES

1. van der Helm FCT, *Journal of Biomechanics*. **27**:551-69, 1994.
2. Hill AV, *Proceedings of the Royal Society of London B.* **129**:136-195, 1938.
3. Huxley AF, *Progress in Biophysics and Biophysical Chemistry*. **7**:255-318, 1957.
4. Zahalak GI, *Mathematical Biosciences*. **55**:89-114, 1981.
5. Cole GK., *Journal of Biomechanics*. **29**:1091-1104, 1996.