ANALYTICAL APPROACH FOR EVLAUATION OF THE SENSITIVITY OF A HILL BASED MUSCLE MODEL

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INTRODUCTION

Hill muscle models are commonly used in musculo-skeletal models to predict muscles forces (Zajac 1989). In this study three common elements will be discussed. The contractile element (CE) generates force, taking into account force-length and force-velocity muscle properties. The series elastic element (SE) models the tendon, aponeurosis, and soft tissue stretch. The parallel elastic element (PE) models the passive properties of the muscle fibres. No one study includes all of the parameter values necessary to describe properties of the muscle; they must be compiled from several sources. Due to the multifactorial nature of the muscle model, only a qualitative evaluation of the sensitivity of such a model to changes in muscle parameters has been done (Scovil & Ronsky, 2002). This study presents a quantitative method to evaluate the sensitivity of a Hill model to changes in its parameters using partial derivatives. In addition to giving a quantitative evaluation of the sensitivity given one set of muscle parameters, the partial derivative calculation also indicates the sensitivity over a continuous range of parameter values.

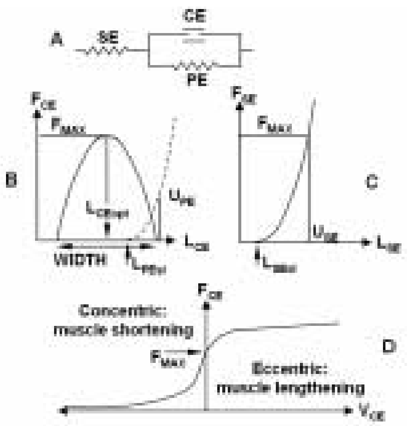

Figure 1: Hill muscle model. See text, Table 1 for abbreviations. A) Component model B) Force length properties of the CE (solid) and PE (dotted) C) Force length curve of the SE D) Force velocity curve of the CE

METHODS

The Hill based muscle model (Fig. 1) equations described in Nagano & Gerritsen (2001) were used. The partial derivatives of the model outputs; the force in the muscle (F_{MUS}), and the velocity of the contractile element (V_{CE}) were taken for each of the model parameters. The partial derivative is a measure of the slope of a curve in the direction of that variable. i.e.

$$\frac{\partial F_{MUS}}{\partial X} = \text{rate of change of } F_{MUS} \text{ for a small change in } X$$

This value was calculated with respect to each of the model parameters (Table 1), and evaluated over the range of muscle model inputs for the given motion - the lengths of the muscle (L_{MUS}) and the contractile element (L_{CE}). L_{MUS} and L_{CE} were taken from the forward dynamics running simulation of Wright *et al.* (1998) to ensure a physiologic range of values. The partial derivative for each muscle throughout running was then calculated. An average of each partial derivative over all muscles and timepoints during stance was evaluated. The standard deviation of the partial derivative was taken within each muscle, then a pooled standard deviation was compiled between muscles. Results were split into the sensitivity levels (Table 1 caption) from Scovil & Ronsky (2002) for comparison and evaluation.

RESULTS AND DISCUSSION

The partial derivatives of this Hill muscle model were successfully evaluated. The techniques presented were evaluated for a particular running model, but are generic, and can be applied to other motions, and other parameter ranges. The partial derivatives of the series elastic element parameters were very large for muscle L_{CE} and L_{MUS} values that occur during running. (Table 1) This implies that the constants L_{Sesl} and U_{SE} must be chosen with great care, as their values will strongly affect muscle force and velocity. This is also true for the partial derivatives with a large effect, L_{CEopt} and F_{ASYMP}. These quantitative results are similar to the qualitative results found by Scovil & Ronsky (2002). Two parameters, F_{MAX} and WIDTH, had large qualitative effects on model outputs, but have a small partial derivative. This difference between techniques may imply that the sensitivity levels for the qualitative study should be refined. This study presents a quantitative approach to Hill muscle model evaluation that provides a generic, continuous equation that can be applied to other motions and models.

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ACKNOWLEDGEMENTS: W Herzog, NSERC, AHFMR

Parameter	Definition	Partial Derivative Evaluation	
A_{REL}	constant in hyperbolic FV equation	0.08 (0.31)	Small
B_{REL}	constant in hyperbolic FV equation	-0.002 (0.041)	Small
F_{ASYMP}	force where the FV curve becomes asymptotic	1.6 (4.7)	Large
F_{MAX}	maximum isometric force	0.29 (0.29)	Small*
L_{CEopt}	length of fiber (the CE) at F_{MAX}	3.6 (16.4)	Large
L_{PEsl}	slack length of the PE	$-6.1e^{-6}$ ($2.6e^{-4}$)	None
L_{SEsl}	slack length of the SE	$-1.2e^{6}$ ($2.7e^{6}$)	Extreme
SF	eccentric/concentric FV curve slopes as $V \to 0$	-0.040 (0.072)	Small
SL	slope of asymptote in FV curve	$3.6e^{-4}$ ($1.5e^{-3}$)	None
U_{PE}	force in PE at max. L_{CE} before F = 0	$-7.5e^{-5}$ ($3.0e^{-3}$)	None
U_{SE}	stretch in SE at F_{MAX}	$-6.1e^{3}$ ($8.4e^{3}$)	Extreme
WIDTH	width of parabola in FL curve	-0.26 (0.87)	Small*

Table 1: Parameters in the muscle model. Derivative presented as mean (standard deviation) over one running step. Sensitivity of the model from changes due to perturbation: **None:** less than 1% **Small**: much less than change **Large:** larger or similar magnitude **Extreme:** larger by a factor of 20 or greater. * marks change from Scovil & Ronsky (2002)