MUSCLE DYNAMICS DURING MONKEY SACCADIC EYE MOVEMENTS AND SIMULATED SACCADIC EYE MOVEMENTS

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ABSTRACT

Actual muscle forces measured during movements can enhance our understanding of neuromuscular control. In this study, we analyzed forces recorded in the intact lateral rectus (LR) and medial rectus (MR) of a monkey during horizontal saccadic eye movements. The results were compared with simulated muscle responses generated from a reciprocal Hill relationship muscle model. We found the muscle force data consistent with our basic understanding of the saccadic system, but not consistent with the simulated responses.

INTRODUCTION

The saccadic eye movement system is a unique system in which to study motor control. It has a simple biomechanical structure; there are no dynamic load changes to consider, and eye position can be measured with great accuracy. Both the neural inputs and many macroscopic muscle properties have been characterized.

Saccades are very stereotyped high velocity movements which function to switch the visual fixation point. They show a characteristic size-dependent peak velocity-duration relationship; in large saccades, as saccade magnitude increases, the duration of the movement increases while peak velocity saturates. Neural recordings show the agonist inputs have a high frequency burst followed by an increase in steady state firing rate (pulse-step pattern). It is believed the pulse is necessary to drive this highly damped system at high velocities, while a much smaller change in innervation is necessary to hold the eye in the new position.

The medial and lateral recti basically drive horizontal saccadic eye movements. Consequently, this restricted class of movements has been modelled by several researchers using variations of two Hill muscle models attached to a mass,spring, dashpot combination representing the globe, surrounding tissue, and passive muscle properties (see [1] for review). We use a model developed by Lehman and Stark; this particular model was selected because it produces realistic eye position and velocity waveforms, and it has been well analyzed and subjected to an extensive sensitivity analysis [2].

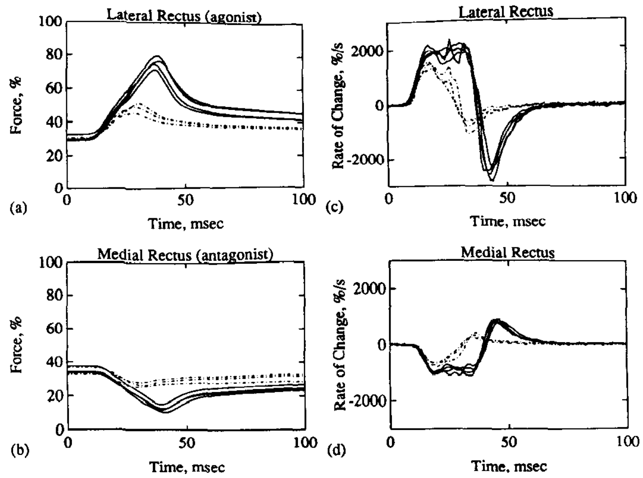

Figure 1. *Force (a-b) and rate of change of force (c-d) recorded in the lateral and medial recti of a monkey during 10 (-.) and 20 (-) degree horizontal saccades. Force is scaled as a percentage of the daily range.*

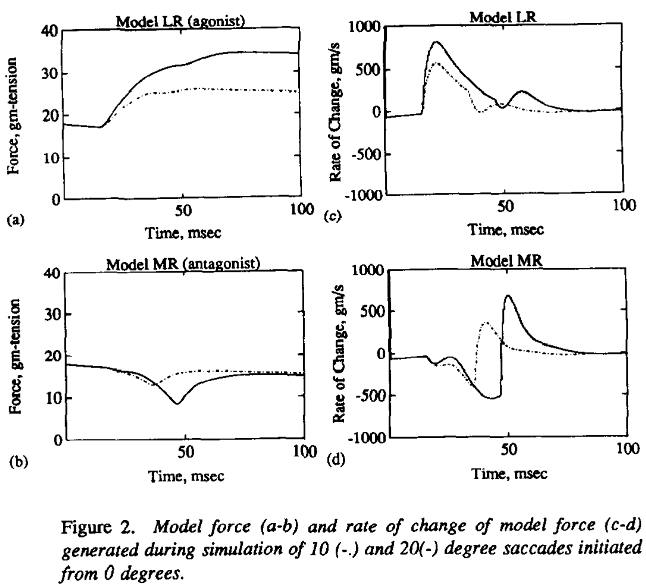

Figure 2. *Model force (a-b) and rate of change of model force (c-d) generated during simulation of 10 (-.) and 20(-) degree saccades initiated from 0 degrees.*

METHODS

A trained monkey performed saccadic eye movements. Forces were measured in intact lateral and medial recti with chronically implanted force transducers [3], and eye position was recorded using the magnetic field/eye-coil technique [4]. An 1000 hz sampling rate was used. The eye position records were filtered and digitally differentiated. The force records were scaled as a percentage of the daily range and digitally differentiated. Finally, the model was simulated with Simnon [4], a nonlinear dynamic system simulation program. Forces generated in the series elastic component of the hill muscles were stored and compared with the actual force data.

RESULTS

Figure 1 shows forces and differentiated force curves recorded during 10- and 20-degree saccades initiated from primary position. A basic symmetry exists in the shape of the LR (agonist) and MR (antagonist) responses and in their differentiated responses. Large differences exist in the peak force necessary to drive 10- and 20-degree saccades, yet only small differences exist in the forces necessary to maintain fixation. The rate of change of force has an initial rapid increase (LR) or decrease (MR). During 20-degree saccades, the initial phase is followed by a plateau phase. The next phase shows a rapid reversal in rate which drives the rate to a negative (LR) or positive (MR) peak; the magnitude of the this peak reversal of force rate is greater for 20-degree saccades.

Figure 2 shows simulated forces and differentiated force curves during 10- and 20-degree saccades initiated from 0 degrees. The shapes of the LR (agonist) and MR (antagonist) forces are very asymmetrical. There is a large difference in LR force required to maintain fixation after 10- and 20-degree saccades. No plateau phase exists in the differentiated force curves. The MR trace shows a rapid reversal which drives the rate from it's negative peak to it's positive peak; and the magnitude of this peak rate is greater for 20-degree saccades. However, the LR doesn't show this reversal phase.

DISCUSSION

The large forces driving the movement and the small forces maintaining fixation are consistent with our understanding of the pulse-step innervation pattern. Also, the plateau in rate of change of force is consistent with the velocity saturation observed during large saccades. The rapid rise to a positive peak rate of change in the antagonist force coupled with the rapid fall to a negative peak in rate of change of force in the agonist shows the braking exhibited by the muscles. This is a characteristic one would expect to see in time optimal movements. However, this is apparently done without a specific braking pulse in the neural command [5].

Surprisingly, the model output was not consistent with the recorded forces. No single parameter change accounts for the differences between model responses and the data. Because the force-velocity relationship is the most poorly characterized muscle property, we suggest this as the starting point for future model development. We may find that time dependent properties, not represented in the force-velocity curves, play an important role.

Of course, a different force-velocity relationship would not account for the large agonist fixation force, but it could have a significant affect on the dynamics of the movement.

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ACKNOWLEDGMENTS

This work was supported by NIH T32 GM07379, NIH/NEI EY06973 to J.M. Miller (and Core Facilities Grant EY06883), EY06860.

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CH3068-4/91/0000-1705 $01.00 © 1991 IEEE