Strabismus 0927-3972/03/$ 16.00

Strabismus – 2003, Vol. 11, No. 4, pp. 205–211

Accepted 25 August 2003

No oculomotor plant, no final common path

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Abstract The assumption that there is an *oculomotor plant*, a fixed relationship between motoneuron firing rate and eye position, is disproved by brainstem recording studies showing that this relationship depends on which supernuclear subsystem determines firing rate. But it remains possible that there is a *final common path* (FCP), a fixed relationship between firing rate and muscle force. But then, brainstem recording studies predict that lateral rectus (LR) forces (and probably medial rectus (MR) forces, as well) will be *higher* in converged than in unconverged gaze for a given eye position. We recently measured these forces and found that they are slightly *lower* in convergence, disproving the FCP hypothesis. Thus, even the relationship between motoneuron firing rate and muscle force is under supernuclear control. What peripheral oculomotor articulations could vary the relationship of firing rate to muscle force?: (1) Actively movable EOM pulleys could alter oculorotary muscle force for a given oculorotory innervation by altering muscle lengths. (2) 'Outer' motoneurons may function as gamma efferents in conjunction with palisade endings and non-twitch global EOM fibers. (3) Complex nonlinear interactions likely arise among both parallel and serially connected muscle fibers.

Key words Co-contraction; convergence; extraocular muscle; final common path; oculomotor plant; ocular rotation; pulley movement

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Acknowledgements:
This work was supported by the Smith-Kettlewell Eye Research Institute and National Eye Institute grant EY-13443 to Joel M. Miller.

Introduction Remarkable progress has been made in understanding central oculomotor and visuomotor processes by assuming that the motoneurons and everything peripheral to them constituted a slavish *oculomotor plant* with a simple, stable, machine-like relationship between ensemble motoneuron firing rate and instantaneous eye position that holds for all types of eye movement.[1,2] This assumption also impeded progress in certain respects because it led investigators to look only to central processes to understand the complex rotational kinematics exhibited by the eye moving in its various modes. Plant articulations began to receive more attention when Miller et al. first proposed the modern notion of extraocular muscle pulleys[3] and obtained the first functional evidence of their existence.[4]

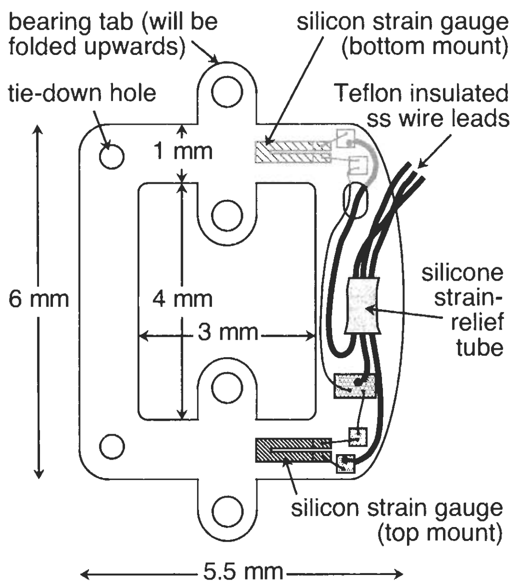
However, studies of vergence eye movement had already disproved the oculomotor plant hypothesis by showing that for a given position of the eye in the orbit mean abducens motoneuron firing rates are higher in converged or near gaze than in unconverged or far gaze.[5–7] The relationship between motoneuron firing rate and eye position, thus, depends on which supernuclear subsystem determines the firing rate.

The motoneurons and extraocular muscles have been called the 'final common path' (FCP),[8,9] following Sherrington, to emphasize that signals from the various supernuclear control centers lose their identities in a single, homogeneous channel. The vergence studies do not refute the FCP hypothesis because, even if there is no fixed relationship between firing rate and eye position (i.e., no oculomotor plant), there still might be a fixed relationship between firing rate and muscle force. However, in that case, the brainstem recording studies clearly predict that lateral rectus (LR) forces will be higher in converged than in unconverged gaze for a given eye position. Further, if the higher LR abducting forces were balanced by higher medial rectus (MR) adducting forces, overall horizontal rectus co-contraction would result. In any case, the prediction of higher LR forces in convergence is an inescapable consequence of the brainstem recording results in conjunction with the FCP hypothesis.

Muscle forces in convergence Recently,[10] we measured LR and MR muscle forces in trained monkeys using chronically-implanted muscle force transducers (MFTs) developed in our lab (Figures 1 & 2).

Fig. 1. Muscle force transducer (MFT) for chronic installation in monkey. Drawing shows the stainless steel frame with tabs, which are bent upward as bearings for a cross-rod that passes under the muscle (see Figure 2). Silicon strain gauges are bonded to the surface and wired in push-pull arrangement to form a half Wheatstone Bridge, providing temperature compensation and summing forces across the width of the muscle.

Fig. 2. MFT installation in monkey. The MFT frame is placed on the oculorotary muscle-tendon, which is tented-up through the frame's central aperture. A stainless steel cross-rod is then pushed through the bearing holes and under the muscle. The braided Teflon-coated leads exit the orbit in the same way as eye coil leads.[12]



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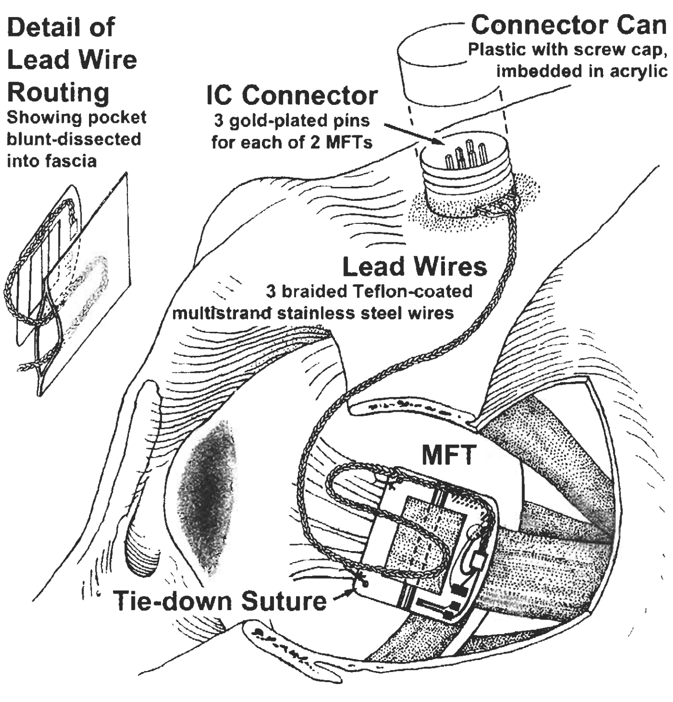

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MFTs measure total oculorotatory muscle force at the tendon, minimally disturb extraocular mechanics, and are not subject to such sampling errors as are inevitable when recording motoneurons or EMGs.[10,11] We trained three *Macaca mulatta* with binocular eye coils[12] and MFTs on the LR and MR of one eye to fixate binocularly for juice reward. All work followed the ARVO resolution on the use of animals in research. In most of our experiments the monkey alternately fixated near (~7 cm) and far (200 cm) targets, arranged to require *asymmetric vergence*, that is, near and far targets are aligned with the instrumented eye (Figure 3), allowing muscle force changes related to convergence state to be isolated, and eliminating any MFT artifacts that might depend on the position of the instrumented globe in the orbit. We defined *convergence force* as the increment in muscle force related to convergence, that is, the force in excess of that which maintains a given eye position with convergence relaxed. Thus, the motoneuron studies predict positive convergence forces.

The closed symbols in Figure 4 summarize the asymmetric vergence data for three monkeys, with each point being the mean of 250–300 vergence movements made in one data collection session. Across monkeys and sessions, mean LR convergence force was –0.49 g, and MR convergence force –0.13 g. From the asymmetric vergence data of one monkey, we extracted and analyzed far and near fixation forces in which left and right eyes were in approximately symmetric positions. These *calculated symmetric* convergence forces are shown as a plus sign (+) in Figure 4, where they can be seen to be similar to the

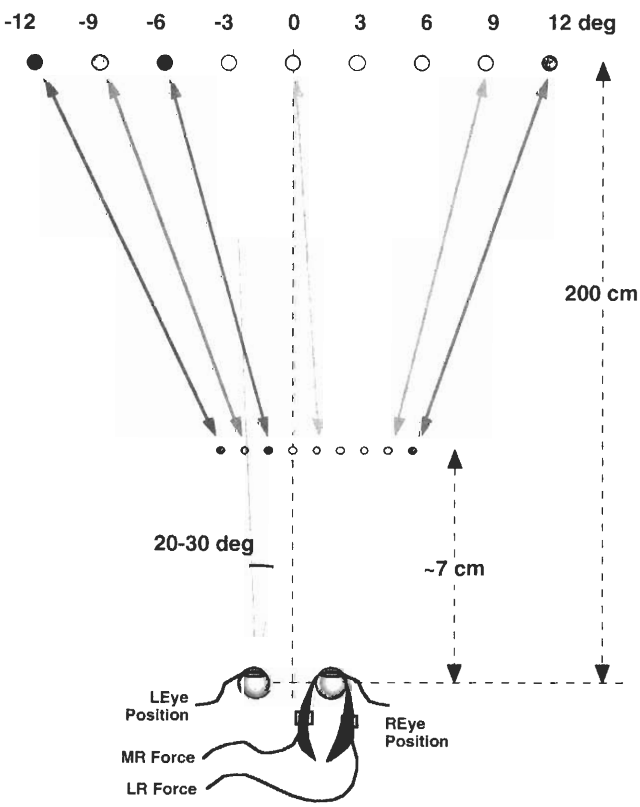

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Fig. 3. Target positions. Near and far targets shown in black are aligned with the instrumented right eye. For symmetric vergence experiments we presented the 'o°' far target and centered a near target on the dotted midline. Targets are labeled with their angular eccentricities at the instrumented eye (the right eye in the figure), with o straight ahead. Figure not drawn to scale.

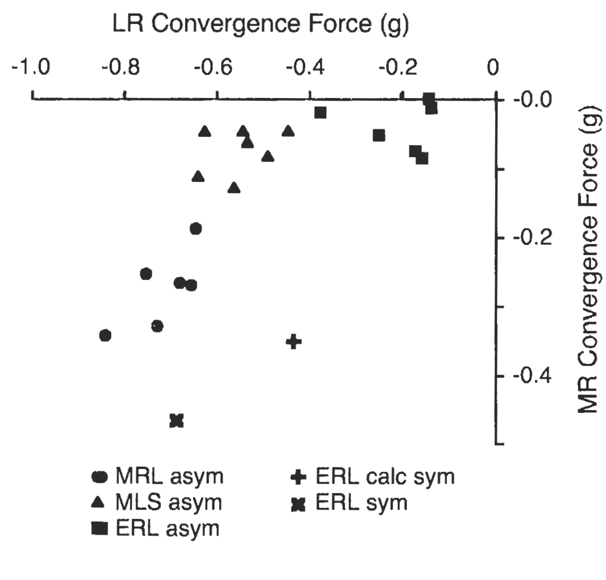

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Fig. 4. Convergence forces. These are the force differences for an instrumented eye in the same position fixating near compared to far targets. 'Asym' = data from asymmetric vergence movements; 'calc sym' = symmetric fixation data extracted from asymmetric vergence sessions; 'sym' = data from symmetric vergence movements. Both LR and MR convergence forces are always negative.

asymmetric convergence forces. Finally, data from six sessions of actual symmetric vergence movements are shown with a cross (**x**). In every session, mean LR and MR convergence forces were negative.

To review, Mays & Porter,[5] Gamlin et al.[6] and Zhou & King[7] found that LRMNs fire at higher rates in convergence than in distant fixation for a given ipsilateral eye position. From the FCP hypothesis, one would certainly expect to measure positive LR convergence forces. To the contrary, we found small (<1 g) *decreases* in LR forces in convergence. Our finding of 'missing LR force' (higher LRMN firing rates in convergence but lower LR forces) is supported by our finding that there is no MR co-contraction. Thus, our findings clearly contradict the prediction that LR forces are higher in convergence. If the motor nucleus recording studies and the muscle force measurements are both correct, then LRMN firing rates do not predict LR muscle forces, disproving the FCP hypothesis by demonstrating that even the relationship between motoneuron firing rate and muscle force is under supernuclear control. How is this possible?

Actively moving EOM pulleys Rectus muscle pulleys deflect EOMs and serve as functional origins with respect to their pulling directions.[3] Demer builds on this basic notion by proposing several *active pulley hypotheses* (APH), which describe modes in which pulley position might be controlled by smooth and striated muscles.[13] Differential control of pulley and eye positions could affect the relationship of motoneuron activity to oculorotary muscle force in two ways. First, some motoneurons might alter their activities without directly affecting oculorotary forces because they innervate EOM fibers connected to pulleys, rather than to the eye. Second, oculorotary forces could change without changes in the activities of oculorotary motoneurons because pulley movements have altered muscle paths so as to alter muscle lengths. EOM force is a function of muscle length as well as innervation, because muscle length affects both the contractile force component (there is an optimal length for force generation) and the elastic force component.[14,15] But although pulley movements have been demonstrated,[16] differential control of pulley and eye movement has not.

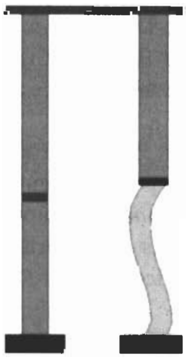
Dual EOM control Büttner-Ennever et al. discovered *outer motoneurons* surrounding the classical *inner motoneurons* of the abducens, oculomotor, and trochlear nuclei,[17] which receive distinct premotor inputs suggesting that they are involved in gaze holding, pursuit, and the near-response, of which convergence is a component.[18] Outer motoneurons multiply-innervate slow EOM fibers and, although their function has not been demonstrated, there are several ways in which they might be involved in modulating the relationship between inner motoneuron firing rate and muscle force. First, if outer motoneurons that innervate orbital layer slow fibers[19] differentially controlled pulley positions, they might affect oculorotary muscle forces as discussed above. Second, outer motoneurons also innervate global layer slow fibers,[19] which are uniquely associated with sensory palisade endings[20] and which Robinson[21] suggested might function like muscle spindles. Such a proprioceptive feedback mechanism might allow the gaze-holding, pursuit and vergence systems to modulate the relationship between inner motoneuron firing rate and muscle force. There is evidence that the vergence system drives abducens motoneurons differently than the conjugate gaze system. King et al.[22] have shown that as vergence angle increases, abducens motoneuron thresholds decrease.

Muscle fiber interactions Goldberg et al.[23] used motor nerve stimulation in the cat to show that 25% of lateral rectus motor units contributed only 50% of their twitch force to an aggregate of nerve-activated units. This means that the force exerted by a motor unit at the tendon depends on the activity of other motor units. McClung et al.[24] showed that for monkey LR, whole muscle twitch and maximum tetanic forces are only 1/20 of that expected from summation of single units.

Polyneural innervation of single muscle fibers may explain subsummation. It is also possible to show that complex nonlinear interactions can arise even among parallel muscle fibers, not to mention among fibers with serial and mesh-like connections.[23,25,26]

Mammalian skeletal muscles with long fascicle lengths are typically composed of short fibers that terminate midbelly in 'steps', with collagenous bridges or myomyonal junctions to neighboring fibers, and no direct connection to the muscle origin or insertion.[27] By counting the fibers in multiple cross-sections from origin to insertion in monkey and human, Oh et al.[28] showed that most EOM fibers do not reach either origin or insertion.

The existence of mechanical, and possibly innervational, interactions among muscle fibers might underlie complex relationships between innervation and force. The tendon force produced by innervating a given set of fibers would depend on the contractile states of other fibers. Variations in recruitment order would not only have direct effects on muscle force, but also indirect effects on the forces produced by other motor units, including those whose recruitment order is unaltered. If recruitment patterns differ for different types of eye movement, resultant muscle forces could vary widely for a given overall firing rate.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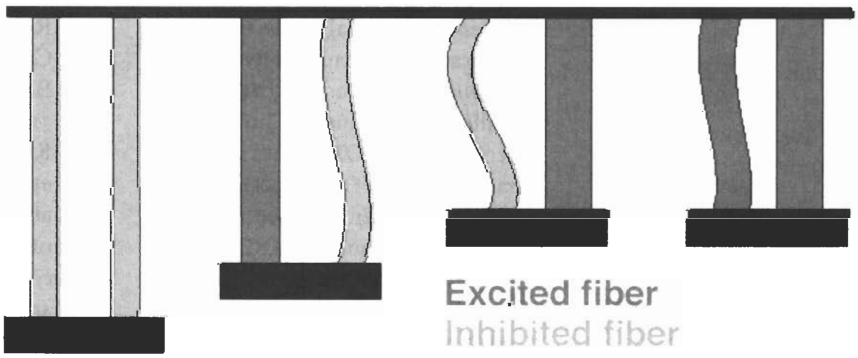

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Fig. 5. Serial fibers (isometric case). It is obvious that if one of a pair of fibers in a mechanical series is relaxed (white), the other, though innervated (dark), may deliver no force to their load.

Fig. 6. Parallel fibers (isotonic case). Less obviously, even parallel fibers will deliver less than the sum of their individual forces to their load if they shorten unequally.

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