

BIOFEEDBACK AND DIFFERENTIAL CONDITIONING OF RESPONSE PATTERNS IN THE SKELETAL MOTOR SYSTEM

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While biofeedback techniques are being extensively applied in operantly conditioning an impressive variety of central and autonomic nervous system responses, our ignorance of the neural mechanisms underlying operant learning remains virtually complete. Indeed, we still have the most elementary and speculative conception of how the nervous system initiates a simple voluntary motor response, no less how the occurrence of such a response can be modified by reinforcement. Our understanding of neural mechanisms underlying operant responding will probably advance soonest in the skeletal motor system, for several reasons. A basic understanding of the neural pathways converging onto spinal motoneurons has emerged from a century of anatomical and electrophysiological studies. More recently developed experimental techniques now make it possible to study activity of identified neurons in awake animals trained to perform relevant motor responses. In such experiments, biofeedback techniques could prove particularly useful in investigating functional relations between elements of the skeletal motor system. We will first review some relevant facts concerning the functional organization of the final elements in the skeletal motor system and then consider past and potential applications of biofeedback techniques to investigate this system.

FINAL ELEMENTS OF SKELETAL MOTOR SYSTEM

Figure 1 diagrams some of the basic elements of the peripheral skeletal motor system which are of present concern. The functional peripheral element is the motor unit, comprised of a single motoneuron and its asso-

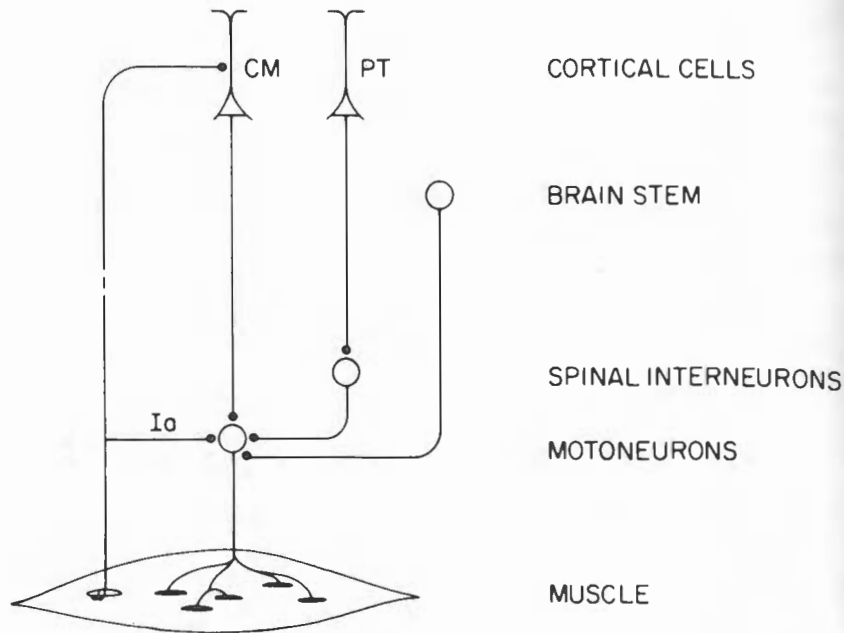


Figure 1. Schematic representation of the final elements of the skeletal motor system considered in text. A motoneuron and its associated muscle fibers comprise the motor unit. Motoneurons are influenced by cortico-spinal cells, both monosynaptically via corticomotoneuronal (CM) cells and polysynaptically via other pyramidal tract (PT) cells which synapse on spinal interneurons. Presence of sensory feedback loops and other descending motor systems are also indicated.

ciated muscle fibers, all of which are activated as a unit when the motoneuron fires. Skeletal limb muscles typically are comprised of several hundred such motor units. Activity of each unit produces a contractile twitch tension which summates with the twitch tension of other units to produce the net force output of the muscle. Depending on load, this force then produces a change in the muscle length and of the limb position. As net active tension increases, motor units appear to be recruited in a systematic sequence, in order of increasing motoneuron size (Henneman, Somjen, & Carpenter, 1965). In general the relation between electromyographic (EMG) activity of a muscle and net tension is not linear, but under isometric conditions, ($\Delta P=0$), net tension is approximately proportional to rectified EMG activity.

The neural pathways converging onto the motoneuron arise from cells in diverse areas: spindle receptors of the same muscle, spinal interneur-

ons, brain stem nuclei, and cerebral cortex. The relative functional importance of each of these systems remains of current experimental interest. A convenient candidate for study in behaving animals are the corticospinal or pyramidal tract (PT) cells, which arise primarily from motor cortex. In the primate some PT cells terminate directly on motoneurons (Kuypers, 1960). The excitatory potency of the corticomotoneuronal (CM) synapse has been demonstrated by stimulating cortex and recording intracellularly the evoked membrane potentials in individual motoneurons. Maximal stimulation, activating all of the cortical cells converging onto a motoneuron (called the motoneuron's "colony") typically produces a depolarization of 2-3 millivolts in forelimb motoneurons of the baboon, insufficient by itself to activate the motoneuron (Phillips & Porter, 1964; Preston & Whitlock, 1961). Less intense cortical stimuli recruit fewer CM cells and evoke smaller EPSPs. Minimal EPSPs are on the order of 100 microvolts (Porter & Hore, 1969), comparable to those produced by single Ia afferent fibers (Mendell & Henneman, 1971). Repetitive activation of the corticospinal cells is nevertheless quite effective in eliciting motor responses (Porter, 1970).

In addition to this basic corticomotoneuronal connection, one must remember the existence of the following important elements: proprioceptive feedback from muscle receptors to both motoneurons and supraspinal cells, other descending systems from brainstem (rubrospinal, reticulospinal, vestibulospinal) converging onto the motoneuron, and higher order cells converging on PT cells. These complexities defeat efforts to generate a simple neural model of motor control and certainly preclude any notion that motor cortex cells are the final controllers of motoneurons. Nevertheless, understanding the role of motor cortex cells in movements is an important first step, and a variety of experimental strategies have been applied to investigating the functional relations between motor cortex cells and motor units.

BASIC BIOFEEDBACK PARADIGM

Before considering applications of biofeedback techniques to investigating corticomotoneuronal relations, it is worth reviewing the basic variables found in most biofeedback studies, as diagrammed in Figure 2. Biofeedback experiments involve a reinforced response, R+, which is the activity on which reinforcement (S^R) is contingent. As the biofeedback literature attests, a large variety of CNS and ANS responses have served as reinforced responses. In addition to the reinforced response, there is also a set of responses which occur simultaneously, but which are not directly reinforced, namely, the correlated responses (RO). The subject is also exposed to several relevant stimuli which potentially affect the subsequent

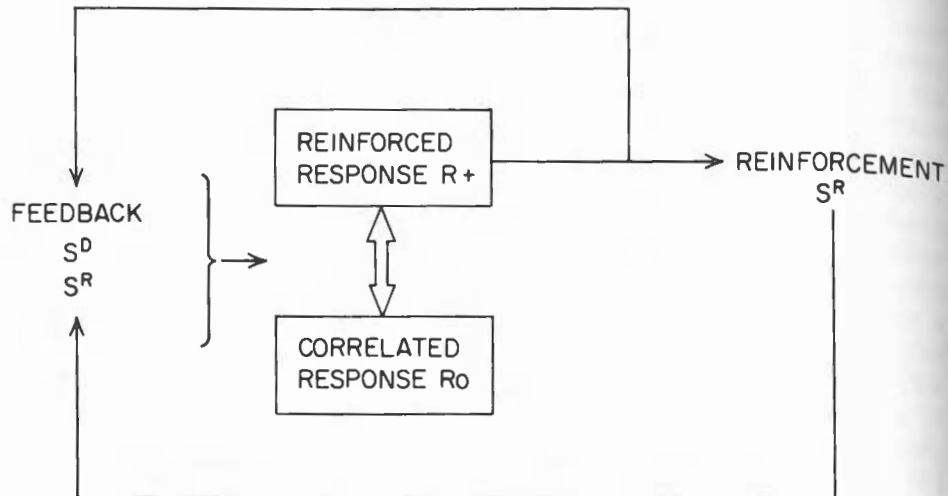


Figure 2. Schematic of basic variables in biofeedback experiments. Reinforcement (S^R) and exteroceptive feedback are contingent upon occurrence of the reinforced response ($R+$). Correlated responses (R_0) which occur in association with $R+$ may have a variety of functional relations with $R+$ (see text). The discriminative stimuli (S^D), reinforcement, and feedback may affect subsequent responses directly, as well as through operant conditioning.

responses. The first is the reinforcing stimulus (S^R), e.g., food, intracranial stimulation, etc.; and the discriminative stimuli (S^D) which signal the availability of the reinforcer. Of course, the essential element in biofeedback experiments is the exteroceptive feedback concerning the value of the reinforced response. By having explicit auditory or visual feedback concerning otherwise unconscious responses, the subject can better learn to control these responses. The diagram suggests that these stimuli may potentially affect subsequent responses. These stimuli could have unconditioned effect on either the reinforced or the correlated response. For example, intracranial stimulation reinforcement has a general arousing effect on motor responses; visual feedback may desynchronize alpha waves; etc. These effects need to be controlled by use of noncontingent reinforcement or, better yet, bidirectional conditioning of the reinforced response.

The relations between $R+$ and R_0 are often of considerable experimental interest. The reinforced response may be either causally or adventitiously related to the correlated response. Among the causally related R_0 are those which produce, or "mediate," $R+$; those which are produced

by R+; and those which may be produced along with R+ by yet another RO. Any of these possibilities produce a correlation between RO and S^R which tends to sustain the occurrence of RO. Besides such causal relations, the simultaneous occurrence of RO may also be accidental; in this case, its occurrence could be superstitiously maintained. However, independent fluctuations between RO and S^R should tend to make RO eventually drop out, i. e., spontaneously dissociate from R+. The nature of the functional relations between R+ and RO can often be further tested by preventing the occurrence of RO (e. g., by paralyzing agents) or by differentially reinforcing the occurrence of R+ in the absence of RO (making RO now part of a more extensive reinforced response, R+₂).

INVESTIGATIONS OF SKELETAL MOTOR SYSTEM

Many experiments on the functional relations between the final elements in the skeletal motor system (Figure 1) may be understood in terms of the above concepts. A common experimental strategy is to reinforce particular movements (R+ = position or force trajectory) and observe correlated activity of motor units or motor cortex cells. For example, to investigate the relation of motor units to force, a useful motor response is a gradual increase in muscle tension. As net tension increases, new motor units are recruited into activity and the firing rate of active units increases slightly. Each motor unit has a specific level of net tension at which it is recruited; this means that each unit has a fixed recruitment order relative to other motor units of that muscle. This recruitment order appears to be the same, independent of which pathways are used to activate the motor units (Henneman, Somjen, & Carpenter, 1965). Moreover, motor units appear to be recruited in order of increasing size. This relationship --called the "size principle"--implies that any convergent pathway to a muscle affects all its motoneurons equally. If true, this principle represents an enormous simplification in the functional organization of motoneuron pools. Consistent with this hypothesis is the finding of Mendell and Henneman (1971) that single Ia afferent fibers send terminal connections to virtually all homonymous motoneurons. Whether this principle can be violated by trained voluntary effort remains an important experimental issue. The prediction that the recruitment of a given unit invariably occurs at a fixed level of net tension could be tested by attempting to dissociate motor unit activity and net tension. Another testable prediction is that two units of the same muscle with substantially different recruitment levels could not be activated without the lower threshold unit. Harrison and Mortensen (1962) and Basmajian (1973) reported that any of several motor units in hand muscles could be activated in isolation under conditions of free limb movements. Henneman, Shahani, & Young (1976) attempted to repli-

cate these results, without success in 6 of 9 subjects; 3 subjects had sporadic, but unreliable, success in activating either of two units whose recruitment levels were close. Hannerz (1974) has shown that rapid phasic contractions may sometimes preferentially activate high threshold units, but confirms the difficulty of doing this under maintained levels of force. Further direct tests of the size principle using appropriate biofeedback would clearly be of considerable experimental interest.

The strategy of reinforcing specific movements has also proven useful for investigating correlated responses in motor cortex cells. In monkeys trained to move a handle through similar displacements but against different loads, Evarts first observed that activity of many precentral PT neurons covaried more strongly with the net force exerted or its derivative than with displacement (Evarts, 1967, 1968). Precentral cells related to jaw movements showed a less consistent relation to force, being strongly activated during the initial reaction-time bite, but sometimes being negligibly related to subsequent force components (Luschei, Garthwaite, & Armstrong, 1971). Humphrey, Schmidt, and Thompson (1970) found that both force and position parameters of a recurrent wrist movement could be predicted from the weighted average activity of a population of precentral cells, with an accuracy increasing with the number of cells included.

While these studies confirm that activity of precentral cells is correlated with movement, the details of the unit-muscle relationships remain unresolved. Interpretation of motor cortex cell responses typically proceeds in terms of the simplest view--namely that these cells are directly involved in activating specific muscles. Consistent with this view are those cells covarying closely with major agonists of the movement. Other cells, whose activity exhibits more complex or less intense covariation with the pretrained movement are often assumed to be directly related to other muscles, whose involvement is correspondingly less direct. While this model may be true for some precentral cells, it risks oversimplifying the relation of many motor cortex cells to movements.

The issue in question concerns the topographical relations between specific precentral cells and muscles. It is quite conceivable, for example, that a given motor cortex cell may be functionally related to activation of several different limb muscles. Moreover, it may be related in more subtle ways than simple covariation. To investigate such questions, biofeedback conditioning techniques have been used to train monkeys to contract specific arm muscles in isolation, and correlated activity of motor cortex cells was observed (Fetz & Finocchio, 1971, 1975). In these experiments, there was a set of {R+} consisting of isolated, isometric contrac-

tions of four representative arm muscles--a flexor and extensor of wrist and elbow--and the correlated response, RO, was the activity of specific motor cortex cells. Isolated muscle activity was differentially reinforced by using a voltage proportional to the weighted sum of activity in all muscles, the weights being positive for the muscle to be activated and negative for the muscles to be suppressed. Besides receiving fruit juice reinforcement when this voltage exceeded a threshold, the monkey had continuous visual feedback via an illuminated meter whose deflection was proportional to the voltage. After several weeks of training the monkey could be rapidly shaped to activate any of the four muscles in relative isolation. In these experiments, most motor cortex cells were found to become active with more than one of the four arm muscles. For example, a single precentral cell could be activated with either the wrist flexor or elbow flexor. Other PT cells were activated with both biceps and triceps, i. e., antagonists of the same joint. Still others were active in the same way with all four muscles, suggesting stronger relation to the occurrence of the response than its topography. These results suggest that many motor cortex cells have a higher order relation to muscles than the one-to-one relation of motoneurons. Figure 3 illustrates the activity of a PT cell which fired with both biceps (Figure 3C) and triceps (Figure 3D) under isometric conditions, but showed negligible modulation in relation to activation of the wrist flexor (Figure 3A) or extensor (Figure 3B).

Experiments in which R+ was a peripheral response (limb movement or muscle contraction) while RO was motor cortex cell activity have revealed that in a given cortical area many motor cortex cells may not be strongly related to the pretrained responses. Whether these cells are related to other responses or not related to any can be investigated by the reverse experimental strategy, namely, reinforcing activity of the cortical cell and observing the correlated motor response (Fetz, 1969; Fetz & Baker, 1973). Using this approach the movement or "motor field" associated with each isolated motor cortex cell can be characterized, much as the receptive field of individual sensory cortex cells can be characterized (Fetz, 1974). When R+ was an operant burst of motor cortex cell activity and RO was free limb movement, a variety of correlated motor responses were observed for different precentral cells. For some cells operant bursts were repeatedly associated with specific movements of a certain joint. For other cells operant bursts occurred with more generalized and variable movements; these movements sometimes became more specific and repeatable as reinforcement of cell activity continued, suggesting that many components of the response which dropped out may have been adventitiously correlated with the cell, whereas the components which remained may have had a stronger, possibly causal relationship with the cell. For other cells operant bursts continued to be associated with a variety of dif-

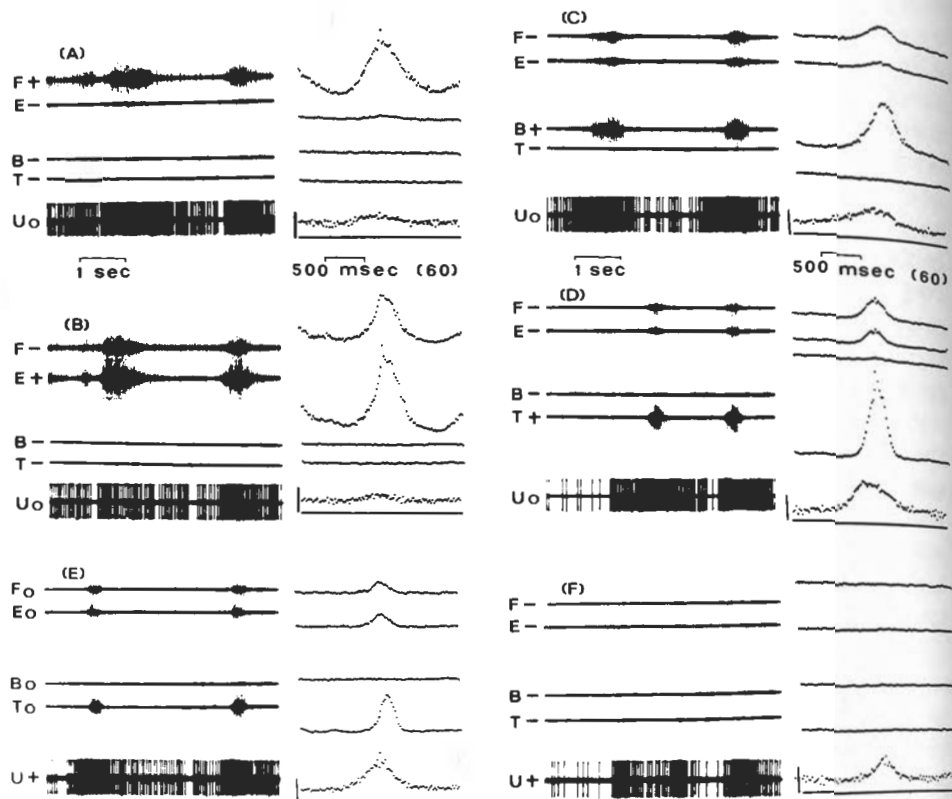


Figure 3. Activity of a precentral pyramidal tract cell and four representative arm muscles during isometric operantly conditioned response patterns. Examples of two successive responses shown at left; averages over 60 responses at right. EMG activity of flexor carpi radialis (F), extensor carpi radialis (E), biceps (B), and triceps (T), and responses of precentral unit (U) are labeled with a "+" or "-" to indicate that activity or suppression of that element was reinforced, and with a "0" to indicate that activity was not included in the reinforcement contingency. (A)-(D): reinforcement of isolated EMG activity in each arm muscle--(A) flexor carpi radialis, (B) extensor carpi radialis, (C) biceps, (D) triceps. (E): reinforced operant unit bursts with associated muscle activity. (F): reinforced unit bursts and muscle suppression. All EMG activity shown at same gain; vertical bars calibrate 50/sec unit firing rate. (From Fetz & Finocchio, 1975).

ferent movements and it was impossible to identify a common component. Finally, some cortical cells were repeatedly activated in operant bursts without any observable correlated motor response. In a given region of motor cortex, examples of each type of cell were found interspersed (Fetz & Finocchio, 1975).

While visual observation of motor responses provides qualitative information concerning the movements associated with operant bursts of a motor cortex cell, recording of EMG activity provides a more quantifiable measure of the extent and time course of correlated muscle activity. The patterns of EMG activity associated with operant bursts of a cell were found to be more repeatable under isometric conditions than under conditions of free limb movement. We have called the set of muscles which are coactivated with operant bursts of a precentral cell the cell's "motor field," as a behavioral analog of the receptive field of sensory cortex cells. For example, when bursts of activity of the cell in Figure 3 were reinforced, the motor field included triceps, flexor carpi radialis and extensor carpi radialis (Figure 3D). Clearly, the unit-muscle correlations seen when the cell was reinforced are not necessarily the same as those seen when muscle activity was reinforced. In Figure 3 the only correlation which consistently appeared under both conditions was the unit-triceps correlation. This correlation was also observed during active extension of the elbow (Fetz & Finocchio, 1975, Figure 6). In contrast, the correlation with wrist muscles appeared only when the unit was reinforced, but not when the wrist muscles were activated. This suggests that some muscles in the "motor field" may not always be consistently correlated under other behavioral conditions. However, the muscle which was most consistently correlated with the cell under different circumstances was usually the muscle which was most strongly activated with operant bursts (e.g. triceps in Figure 3). For the cell in Figure 3, the unit-biceps correlation was the least consistent under different behavioral conditions; unit and biceps activity were positively correlated when biceps was reinforced (3C), not correlated when the unit was reinforced (3E), and negatively correlated during active elbow movements, i.e., the unit was suppressed while the biceps was activated during elbow flexion. This suggests that unit-muscle correlations may depend strongly on the behavioral circumstances, and that they should be tested under a variety of conditions to determine which ones are the most consistent.

DISSOCIATION OF CORRELATIONS

As argued elsewhere (Fetz, 1974; Fetz & Finocchio, 1975), the "strongest" unit-muscle correlations are those which involve the most in-

tense coactivation of cells and muscle and those which appear most consistently under different behavioral conditions. However, even the strongest unit-muscle correlations could be changed by operantly reinforcing their dissociation. Thus, for the PT cell in Figure 3, the unit-triceps correlation, which appeared during triceps activity, unit reinforcement, and active elbow extension, could be dissociated when the monkey was reinforced for activating the cell and suppressing all muscle activity (Figure 3E). Similar dissociation was achieved for all precentral cells tested in this study and appeared to be as easy to shape as isolated muscle activity. Thus, operant reinforcement of the dissociation revealed a degree of plasticity in these correlations which was not apparent when either units, muscles, or movements were the reinforced responses. In retrospect, this result might not be considered surprising since the effect of a single precentral cell, even those which have direct corticomotoneuronal connections, is subthreshold for firing the motoneuron and could in principle be easily overridden by the combined effects of other descending pathways. The fact that these cells and motor units can be so independently activated, however, does reveal an unexpected degree of flexibility in the system. In contrast to motor units, whose activity cannot be readily dissociated--if at all--from activity of homonymous motor units, motor cortex cells appear to have more flexible relations to muscle activity and force. Similarly, pairs of adjacent cortical cells which covaried strongly during both active and passive limb movements could be activated independently when the monkey was differentially reinforced for increasing activity of one cell and suppressing the other (Fetz & Baker, 1973). Clearly, operantly conditioning specific patterns of responses in these cells and muscles provides more extensive and detailed information concerning their functional relations than could be obtained by reinforcing movements alone.

CONNECTIONS REVEALED BY CROSS-CORRELATIONS

The fact that many motor cortex cells covary strongly and consistently with muscle activity raises the issue of their anatomical relationship. Some of these cells may have direct corticomotoneuronal connections; many more probably have indirect connections via spinal interneurons, brainstem neurons, or other corticospinal cells. Strong correlations--in the sense of consistent covariation--between motor cortex cell and muscle activity may suggest a functional relationship, but cannot establish the existence of a direct CM connection. Since many unconnected cells and muscles may be coactivated, such covariation is not sufficient to establish a connection. Moreover, since the effect of a direct CM connection is subthreshold for activating the motoneuron, consistent coactivation is not even a necessary consequence of a connection. An extensive

search for an independent method of establishing connections led to the finding that cross-correlation procedures could be used to detect monosynaptic CM connections. A convenient approximation to a true cross-correlation is the spike-triggered average, which preferentially summates those post-synaptic events consistently correlated with the action potentials triggering the average. Mendell and Henneman (1971) first used this technique to establish that action potentials in single Ia afferent fibers were followed by monosynaptic EPSPs in virtually all homonymous motoneurons. We have found that triggering an average from action potentials of motor cortex cells and summing rectified EMG activity of covarying muscles may reveal the effects of direct CM connections (Fetz, Cheney, & German, 1976). For certain cells, the average EMG exhibits a transient post-spike facilitation (PSF) following the cortical spike at a latency consistent with known conduction times and having a time course resembling the shape of electrically evoked CM-EPSPs (Phillips & Porter, 1964; Preston & Whitlock, 1961). The simplest interpretation of this PSF is that it is mediated by a direct monosynaptic CM connection. Of 201 precentral cells strongly covarying with either flexion or extension of the wrist, 54 were followed by PSF in one or more muscles. The possibility that a single CM cell may facilitate motoneurons of more than one muscle via divergent terminal connections was tested by averaging EMG activity of 5 different synergistic muscles. Of 41 cells followed by PSF in at least one of the 5 muscles, 10 exhibited PSF in more than half of the muscles. Thus, the set of muscles followed by PSF for a given cell--called the cell's "muscle field"--may include at least several different synergists of a joint. Seventy-five percent of the cells had PSF in one or two of the 5 muscles, suggesting more restricted muscle fields.

CONCLUSION

In summary, we now have several fruitful strategies for investigating the functional organization of the final elements of the motor system. The observation of consistent covariation between cells and muscles during certain motor responses provides evidence of a functional relationship. Operantly conditioning specific response patterns in cells and muscles with biofeedback is a particularly powerful technique for testing the strength and stability of such covariations. More recently, the spike-triggered average, as a convenient approximation to a cross-correlation, has proven capable of detecting the existence and extent of anatomical connections. Clearly the most interesting work lies still ahead--namely to combine these techniques to test the covariation of cortical cells whose anatomical connections to motoneurons may be independently established.

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