Functional Classes of Primate Corticomotoneuronal Cells and Their Relation to Active Force

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SUMMARY AND CONCLUSIONS

1. The activity of corticomotoneuronal (CM) cells, identified by clear postspike facilitation (PSF) of rectified EMG activity in spike-triggered averages, was recorded in precentral cortex of monkeys making two types of ramp-and-hold wrist responses. "Auxotonic" wrist movements against elastic loads required active torque proportional to wrist displacement, and isometric responses involved ramp-and-hold torque trajectories with no wrist displacement.

2. On the basis of their firing pattern during the ramp-and-hold responses, all CM cells (n = 135) could be classified into four types: phasic-tonic (59%), tonic (28%), phasic-ramp (8%), or ramp (5%). All CM cells (as defined by PSF) were active during the static hold period; "tonic" cells discharged at a constant rate, while "ramp" cells showed steadily increasing discharge during the hold period. During the dynamic phase of the response, i.e., during the torque ramp, the "phasic" cells exhibited an additional peak of activity exceeding the final tonic level associated with the hold period. Single CM cells exhibited the same response pattern in association with both isometric and auxotonic responses; thus, the torque trajectory rather than displacement or velocity seems to be the primary determinant of the CM cell's response pattern. Other precentral cells, which discharged phasically at onset of movement but exhibited no tonic discharge during the hold period, did not produce PSF. The four types of CM cells did not differ significantly in the size of their muscle field, their response to passive movements, or their location in the cortex.

3. From response averages we measured the onset time of CM cell activity relative to the onset of EMG activity in its facilitated target muscle(s). The phasic-tonic and phasic-ramp cells began firing significantly earlier with respect to their target muscles (mean onset latencies: -71 and -63 ms, respectively) than the tonic and the ramp cells (+5 and +101 ms, respectively). Since the peak PSF occurred about 10 ms after the spike, the initial discharges in many CM cells would contribute to subthreshold facilitation of their target motoneurons.

4. To investigate the relation between firing rate of CM cells and active torque, monkeys were required to exert different levels of active torque for the same displacement. During the hold period the tonic activity of each cell was a linearly increasing function of static torque over all or much of the range examined. The rate-torque slope of CM cells—i.e., the increase in firing rate per increase in static torque in the linear range—was similar for auxotonic responses (constant displacement) and isometric responses (zero displacement). The mean rate-torque slope of all extension CM cells (4.8 impulses·s⁻¹/10⁵ dyn·cm) was about twice that of flexion-related cells (2.5 impulses·s⁻¹/10⁵ dyn·cm). This difference may reflect different degrees of cortical influence on wrist flexor and extensor muscles, although mechanical factors cannot be entirely excluded.

5. Over the range of torque studied, only a few CM cells had appreciable nonzero torque thresholds for tonic firing. Most
cells were inactive with the monkey at rest and during movements opposite their favored direction. Thus most CM cells appear to be recruited at low torque levels; their contribution to increases in active torque is due more to increases in firing rate than to recruitment of additional CM cells with high thresholds.

6. Under isometric conditions, the effect of wrist displacement on the activity of seven CM cells was tested at several wrist positions. For two CM cells the relation to isometric torque was fully documented at three wrist positions. Firing rates of CM cells were higher for positions in which their target muscles were shorter, consistent with the isometric length-tension properties of their target muscle.

7. Some CM cells, whose activity co-varied reliably with controlled ramp-and-hold responses, became less active during rapid ballistic responses, suggesting some differences in neural mechanisms underlying these two types of movement.

INTRODUCTION

The function of motor cortex cells in movements has been investigated by documenting such properties as their firing patterns during specific limb movements (3, 7, 10, 11, 14, 16, 24, 27), their onset times relative to muscles and to cells in other areas (7, 10, 16, 20, 26, 27), and the relation of their activity to certain movement parameters, particularly limb displacement and active force (3, 5, 6, 11–14, 16, 22, 24–27). Even for simple and repeatable limb movements, precentral cells exhibit a great variety of discharge patterns; analysis often focuses on those neurons whose response patterns are most readily interpreted in terms of functional hypotheses. The observed diversity of cell types may be the result of sampling different cells, each related in simpler ways to muscles having diverse relations to the task. Alternatively, there may be an inherent variety of response patterns even for precentral cells directly related to the movement agonists.

The relative timing of cell activity during active movements has been investigated to determine whether neurons in different regions show any consistent differences in recruitment times. Such differences would suggest a sequence of activation in hierarchically related regions preceding generation of a voluntary movement (27). Such studies have revealed remarkably broad distributions of onset times of precentral cells in relation to movement onset (7, 10, 20, 26, 27) and indicate considerable overlap of the recruitment times of cells in motor cortex and other regions (26, 27). Since these experiments sampled neurons with diverse projections, the possibility remains that subsets with similar connections might show a more restricted range of recruitment times.

The relation between activity of pyramidal tract neurons (PTNs) and active force produced at the wrist was first examined by Evarts (5), who found that the discharge of certain PTNs varied with the magnitude of isotonic loads imposed during similar wrist movements. Under isometric conditions PTNs discharged with force, in the absence of displacement (6), leading Evarts to postulate that PTN activity is coded in terms of active muscle force and/or its first derivative. Investigating wrist movements against elastic loads, Schmidt et al. (22) noted that changes in precentral cell activity with different load levels were relatively weak compared with changes that accompanied opposite directions of movement, and suggested that motor cortex may be more involved in specifying the agonists of the movement than the force they generate. Other studies (3, 12, 14, 24, 27) have confirmed that some precentral neurons increase their discharge with active force. All investigators also found many task-related cells whose activity was unrelated to the active forces measured.

A major limitation in interpreting the functional significance of the activity of precentral neurons derives from the uncertainty of their terminal projections. In previous studies the axonal projections of the recorded cells were either unidentified (3, 12, 16, 20, 22, 24, 26, 27) or identified by antidromic activation from the pyramidal tract at the medullary level (5–7, 10, 11, 14, 25). Since even PTNs may not directly affect motoneurons, it seemed worth reinvestigating the firing pattern, recruitment times, and force relation for those pre-
central cells whose effects on motoneurons could be confirmed by spike-triggered averaging (STA). Motor cortex neurons whose action potentials are followed by clear post-spike facilitation (PSF) of average EMG activity, with a strength and latency suggesting mediation by corticomotoneuronal (CM) connections (8, 9), are here referred to as CM cells.

In these experiments, rhesus monkeys were trained alternately to flex and extend their wrists against elastic loads of variable stiffness. On the basis of their firing pattern during the ramp-and-hold wrist responses, four types of CM cells were distinguished. The firing patterns of some CM cells differed substantially from the activity of their target muscles, particularly at onset of the response. These firing patterns were primarily related to active torque since they did not change when displacement was prevented. The tonic firing rates of all CM cells increased linearly with active torque over much of the range studied. Since their activity also demonstrably facilitated the firing probability of motor units, such CM cells contribute causally to generating active wrist force.

METHODS

Monkey training and performance

During recording, the monkey's right arm was strapped firmly in a cushioned cast and the hand was clamped between padded plates with digits extended. The padded plates were attached to the hub of a wheel which was free to rotate 60° in either the flexion or extension direction. The hub was connected to the wheel's outer rim through four ribs with strain gauges to measure the torque developed at the wrist. The monkey's arm was positioned with the wrist joint directly above the rotation axis of the wheel. The wheel's outer rim was fastened to and solely supported by the shaft of the torque motor. This arrangement minimized frictional and inertial loads and detected all external forces acting at the wrist, including those exerted by the monkey to overcome inertia of the manipulandum, friction, and loads applied through the torque motor. Only internal loads arising from the viscoelastic properties of the muscles, tendons, and joints were not detectable.

The strain gauges were calibrated by suspending weights from a fine nylon rope threaded over a low-resistance pulley and attached to the hand plates of the manipulandum, with the outer rim of the rotating wheel locked in position. The torque was computed as the product of force times the radial arm of the attachment point. Strain-gauge sensitivity for both flexion and extension was 1.4 μV/dyn·cm. Wrist position was measured by a potentiometer on the shaft connecting the manipulandum wheel with the torque motor.

Data were collected from three monkeys trained to perform wrist movements against elastic loads (auxotonic movements (23)) and isometric responses. Auxotonic movements consisted of alternate flexions and extensions of the wrist between two electronically detected hold zones. In this task, angular displacements away from the zero position were opposed by torques proportional to displacement; i.e., the servo system simulated an elastic load, whose stiffness could be changed to require different torque for the same displacement. At zero wrist displacement, the hand was aligned with the forearm axis. The extension and flexion zones were both 10° wide. The inner boundary of the extension zone was typically between 15 and 20°; the inner flexion boundary, usually between 25 and 30°.

For isometric responses the manipulandum was locked in position and the monkey was required to generate a torque trajectory alternating between flexion and extension zones. The required isometric torque levels could be varied between 0 and 20 × 10^5 dyn·cm. Visual inspection as well as potentiometer output confirmed that movements were negligible under isometric conditions.

For both of these tasks, visual cues indicated the correct direction to move and a tone sounded when wrist position or torque was within the proper zone. The required hold time in each zone was 1 s.

Since the monkeys performed the movement task longer and more reliably than the isometric task, CM cells were usually sought during auxotonic movements. Well-trained monkeys typically worked daily for 3 or more hours on either task and made over 3,000 successful responses.

Identification of CM cells

Precentral cortex cells were sought while the monkey made wrist movements against moderate to heavy loads to avoid missing cells that might be active only at high torque levels. STAs of rectified EMG activity of covarying wrist muscles were compiled as previously described (8, 9). Neurons were identified as CM cells if STAs revealed a transient PSF of the firing probability of motor units of any of the five to
six coactivated muscles. PSF was evaluated in STAs of 2,000 events or more. Since these cells were recorded during many responses, several consecutive STAs were computed for many cells to confirm the reproducibility of the PSF.

EMG activity of six flexor and six extensor forearm muscles was recorded differentially with indwelling pairs of multistranded wires inserted through the skin with a hypodermic needle. The wires were fixed in position with adhesive tape and provided stable recording for several weeks. Identification procedures are described in the preceding paper (9). The muscles sampled and illustrated include extensors digit two and three (ED2,3) and four and five (ED4,5), extensor carpi ulnaris (ECU), extensor digitorum communis (EDC), extensors carpi radialis longus and brevis (ECR-L, ECR-B), pronator teres (PT), flexors carpi radialis and ulnaris (FCR, FCU), palmaris longus (PL), and flexors digitorum sublimis and profundus (FDS, FDP).

Recording and analysis of data
For CM cells, activity was documented during movements against several different loads. All data, including unit activity, torque and position signals, and covarying EMGs, were recorded on magnetic tape for subsequent analysis. The goal was to study the activity of each cell over as wide a range of loads as possible. All cells included in this report were documented for at least four load conditions. Load levels were not presented in any consistent order. All measurements of torque, unit firing frequency, and onset time of unit activity relative to EMG activity were made from response averages of 20–100 responses compiled off-line. Mean firing rates were also measured from averages of the output of a frequency meter that provided a continuous signal proportional to instantaneous frequency. Response averages were triggered from the onset of the position or torque ramps. Analysis periods of 1.5–3.0 s began about 300 ms before the phasic response. Sampling rates for response averages ranged from 100 to 200 Hz (bin width 5–10 ms). The torque or position signal was applied to an editing circuit, which excluded unsuccessful responses from the averages.

RESULTS
Response patterns of CM cells
The phasic and tonic activity of 135 CM cells during the ramp-and-hold wrist movement was quantified by compiling response averages off-line for different load conditions. All CM cells showed some maintained activity during the static hold period. In contrast, many other precentral cells fired only phasically at movement onset and showed no tonic discharge even with heavy loads. For these phasic cells, STAs of 2,000 or more events failed to reveal any evidence of PSF in the forearm muscles tested.

The response averages of CM cells revealed four basic types of firing patterns during the ramp-and-hold wrist movements. On the basis of their responses during the dynamic and static components of the movements, all CM cells could be classified as phasic-tonic, tonic, phasic-ramp, or ramp. Characteristic examples of each type are illustrated in Fig. 1. The mean firing rate of each CM cell is shown with averages of rectified EMG activity of its facilitated wrist muscles. The response patterns of the four units in Fig. 1 were documented under isometric conditions to demonstrate that the phasic components were not related to overcoming inertial loads.

The most common type of CM cell was phasic-tonic, representing 59% of the documented cells. Phasic-tonic cells exhibited a prominent phasic increase in activity at movement onset, followed by constant firing rate during the static hold; the phasic peak was distinctly greater than the final tonic firing rate, and occurred with the dynamic phase of muscle activity. The wrist torque trajectory always involved a ramp change from flexion to extension torque (or vice versa), with no obvious overshoot; thus, the phasic-tonic pattern was not simply related to a comparable variation in the torque response. The peak of phasic activity in all phasic tonic cells preceded the end of the torque ramp and usually occurred before the midpoint of the torque ramp.

Tonic cells comprised 28% of all CM cells. Their firing pattern showed no phasic peak at movement onset; instead, average activity rose monotonically with onset of muscle activity, attaining a maximum roughly coinciding with the maximum torque. A relatively constant mean level of activity was then maintained throughout the static hold period of the response.

The remaining CM cells exhibited response patterns classified as phasic-ramp or ramp, representing 8 and 5% of the total. Both of these types exhibited average firing
FIG. 1. The four types of response patterns characteristic of CM cells during ramp-and-hold wrist responses. The illustrated responses are isometric torque trajectories; similar patterns occurred when torque was accompanied by wrist displacement. The four categories are distinguished by a) the firing rate during the static hold period, which was either constant (tonic types, top) or increasing (ramp cells, bottom); and b) the presence (left) or absence (right) of an additional dynamic burst response during the initial increase in torque. Also averaged were rectified EMG activity of three coactivated forearm muscles; those facilitated by each cell are indicated by an asterisk. Torque calibration bar: $5 \times 10^5$ dyn·cm. The number of responses averaged for each cell (100) is given in lower right in this and subsequent figures. Response averages were triggered on transition from flexion torque to extension torque.

rates that rose continuously during the static hold period when muscle activity was steady. This increasing discharge could begin before or well after the torque had reached its plateau and rose continuously throughout the entire hold period (maximum duration observed was 2 s). Phasic-ramp cells were clearly distinguishable from ramp
FIG. 2. Isometric and auxotonic responses of the same CM cell, showing that the same phasic tonic response pattern occurred under both conditions. Average EMG of three coactivated muscles includes activity of the facilitated muscle, ED2.3. Torque calibration bar: $5 \times 10^3$ dyn cm. Position calibration bar: 10°.

Most CM cells fell clearly into one of these four categories; however, a few exhibited patterns intermediate between two categories, suggesting that the relevant features may form a continuum. For example, the difference between the magnitude of the phasic component and the tonic component—referred to as the dynamic index (17)—had various values, ranging from zero (for a pure tonic cell) to greater than 100 impulses/s. Also, some ramp cells showed a relatively modest rate of increase during the static hold. A given type of CM cell exhibited the same response pattern independent of the levels of active torque. However, the proportional magnitude of the phasic component relative to tonic firing rate often changed as the load opposing wrist displacement increased.

That these response patterns represent functionally significant classes of cells is further supported by the fact that the cells exhibited the same firing pattern for both auxotonic and isometric responses, as illustrated in Fig. 2. Although the two conditions differ, since auxotonic responses involved displacement of the wrist whereas isometric responses involved no overt wrist movement, this CM cell exhibited a phasic-tonic pattern under both conditions. Similar constancy was found in all eight CM cells tested under both conditions.

We found no clear relation between the response pattern of a CM cell and its target muscles, with respect to either the number of facilitated muscles or their location. The few slow PTNs tested were more dynamically sensitive. One slow PTN, which did not produce PSF, had a phasic-tonic response pattern with a dynamic index exceeding 120 impulses/s. The slow CM cells
were all phasic-tonic, but too few were observed to indicate any statistical trend.

Timing of CM cell activity

Since STAs revealed that CM cells have direct correlational linkages with forelimb muscles, producing peak facilitation of EMG activity at a mean latency of 10.2 ± 3.0 ms (9), it was of interest to compare the onset times of these cells with the onset of activity in their target muscles. Figure 3 plots the onset time of 132 CM cells relative to the onset of EMG activity in their facilitated muscles, as measured from response averages. The response type of each unit is indicated separately. Most CM cells became active between 0 and 120 ms before onset of activity in their target muscles. A significant proportion of cells began firing after the onset of EMG activity; many of these were tonic or ramp cells, although some phasic-tonic cells also became active after their target muscles. The overall mean onset times were 71 ms for phasic-tonic, 63 ms for phasic-ramp, +5 ms for tonic, and +101 for ramp cells. The mean onsets of tonic and ramp cells were significantly later than those of phasic-tonic and phasic-ramp cells ($P < 0.01$).

Torque relation of CM cells

To quantify the firing rate of CM cells as a function of different levels of active torque, the monkeys were required to make ramp-and-hold torque responses of different magnitudes. During auxotonic movements against springlike loads the monkeys achieved approximately the same wrist position with each response; the load was varied by changing the effective spring constant in discrete steps covering the full range of torque achievable by the monkey.

Figure 4 illustrates the firing rate of one CM cell during wrist movements into the same hold zones against different elastic loads. The three response averages at the right were compiled for three load levels, indicated by points a, b, and c on the graph. In this graph and those in Figs. 5 and 7, each data point was measured from an average of at least 20 responses at the same load level. The average tonic firing rate was measured 0.5 s after the end of the torque ramp. The phasic-tonic CM cell in Fig. 4 was
FIG. 4. Relation between mean firing rate and mean torque for a phasic-tonic CM cell. Response averages at right include 100 wrist extension responses against high (a), moderate (b), and zero (c) external load. Tonic firing rate and torque were measured 0.5 s after the end of the wrist displacement ramp. Phasic firing rate was measured at the peak of the phasic burst and is plotted against magnitude of peak phasic torque from the same averages. An example of the PSF produced by this cell (SI86-4) is illustrated by the inset in lower right of graph.

typical in that its tonic rate increased linearly with static wrist torque over more than two-thirds of the torque range studied. The slope of this curve—i.e., the increase in tonic firing rate per increment in static torque—may be called the cell’s rate-torque slope; in its linear range, this cell had a rate-torque slope of 6.3 impulses $\cdot$ s$^{-1}$/$10^5$ dyn $\cdot$ cm. Below $4 \times 10^5$ dyn $\cdot$ cm, activity of this cell showed little relation to torque; in the absence of external load it fired at 20 impulses/s with the wrist extended. Some of this activity may be related to overcoming internal loads associated with wrist displacement, such as stretching antagonist muscles, since the cell was silent with the monkey at rest. The phasic activity of this cell (upper curve) was measured at its peak, which occurred midway through the ramp of movement. At the lower end of the torque range, the peak phasic activity increased steadily with increasing torque; above $8 \times 10^5$ dyn $\cdot$ cm, peak discharge seemed to saturate at about 125 impulses/s. Velocity of movement was essentially the same at all load levels; hence, the rate of change of torque increased as a function of load. Thus, the phasic activity of this cell and others like it may be related to the rate of torque increase.

Figure 5 plots the tonic firing rate as a function of static torque for the extension-related CM cells ($n = 14$) documented at four or more load levels. For each cell, an example of the PSF in one of its target muscles is shown at the right. Each CM cell exhibited a tonic firing rate that increased monotonically with static torque over the whole range of torque levels. Several cells exhibited some activity at the low end of the torque range, although most CM cells were
FIG. 5. Relation between tonic firing rate and static torque for 14 CM cells related to wrist extension. For each cell, an example of the PSF of one target muscle is shown at the right; arrows at top indicate time of triggering spike in CM cell. The number of facilitated muscles is indicated in parentheses. Cells were selected solely on the basis of the strength of their PSF and the adequacy of the range of loads studied. The firing rate of all plotted cells was measured from response averages, compiled for at least four load levels.

inactive in the absence of movement. All CM cells were silent during movements opposite their favored direction, i.e., during torques generated by antagonists of their target muscles. Some cells showed nonlinearities or a transition to a region of different slope at high values of torque. Nevertheless, over some part of the range, the activity of every CM cell increased linearly with static torque.

Of particular interest is the unit SI 64-3 (filled triangles in Fig. 5) since it exhibited a torque threshold for tonic firing. This CM cell, in other words, was recruited at higher force levels, analogous to high threshold motoneurons. Figure 6 shows separate response averages of this cell, with its facilitated extensor muscles, torque, and position at three different load levels. In the absence of any external load, this cell showed no
tonic activity, despite some EMG in all four target muscles. This muscle activity was apparently required to overcome internal loads arising from the viscoelastic properties of tissues being stretched or compressed. Thus, although no external torque was produced under the "no load" condition, the EMG records indicate that some muscle activity was necessary to overcome internal loads. When the external load was increased to a moderate level, involving appreciable EMG activity, this cell still showed no reliable tonic discharge, typically firing only once during the hold period of each trial. When a wrist torque of about $4 \times 10^5$ dyn·cm was exceeded, the cell fired reliably at a mean tonic firing rate, which increased linearly as a function of wrist torque, with a slope similar to that of other extension-related CM cells. While this CM cell clearly had a torque threshold for tonic firing, such a high recruitment level was uncommon for CM cells during either auxotonic or isometric wrist responses. Interestingly, we found several non-CM cells that showed nonzero torque thresholds for tonic firing; since they did not facilitate the agonist muscles, their contribution to the generation of wrist movement remains less certain.

The load relation of all CM cells activated with wrist flexion is plotted in Fig. 7, with examples of the PSF produced by each cell. PSF of most flexion cells tended to be weaker than the PSF of extension cells (9). Activity of flexion CM cells also increased linearly with wrist torque over all or most of the range studied. However, the slope of this linear portion was generally less for flexion-related cells than for extension cells (compare Figs. 5 and 7).

The slopes of the linear portions of the curves in Figs. 5 and 7 are given in Table 1. The rate-torque slope of extension CM cells ranged from 1.4 to 8.0 impulses·s$^{-1}$/10$^5$ dyn·cm, with a mean of 4.8 ± 2.0 (SD) impulses·s$^{-1}$/10$^5$ dyn·cm. In contrast, flexion cells had slopes of 0.6–5.0 impulses·s$^{-1}$/10$^5$ dyn·cm, with a mean of 2.5 ± 1.4 impulses·s$^{-1}$/10$^5$ dyn·cm. The difference in means is statistically very significant ($P = 0.001$). Table 1 also gives the response type and antidromic latency from the medullary pyramid of the CM cells illustrated in Figs. 5–8. No significant correlation is apparent.
between response type or antidromic latency and the torque slope in these data, except that both of the slow PTNs had either the lowest (SI 121-1) or nearly the lowest (SI 130-2) torque slope of all cells in their group. Neither was there any obvious relation between the torque slope of a CM cell and its muscle field; cells facilitating predominantly wrist muscles did not differ consistently from those facilitating finger muscles. Neither did the number of target muscles correlate with torque slope.

It is difficult to estimate what percentage of their maximum possible active force our monkeys exerted during these responses. They were probably capable of transiently producing considerably more torque than the static levels represented on the graphs of Figs. 5 and 7; one monkey occasionally made rapid, oscillating, ballistic wrist movements, during which dynamic torque exceeded $30 \times 10^5$ dyn cm. Nevertheless, the static torques represented in these graphs for extension and flexion seemed to be near maximum levels that could be consistently sustained for ramp-and-hold responses.

Isometric torque relation and effect of wrist position

To document the torque relation of CM cells in the absence of changes in wrist displacement and to measure the effect of wrist position on torque slope, the activity of 10 CM cells was studied under isometric conditions. For comparison, four of these were also documented for several loads during wrist movements. As found for auxotonic responses, the isometric responses of all CM cells had a range over which tonic firing rates were linearly related to static wrist torque (Fig. 8). The mean torque slope of cells studied under isometric conditions did not differ significantly from those obtained during wrist movements (Table 1). This result was further confirmed for two cells documented under both auxotonic and isometric conditions. Figure 9 illustrates...
TABLE 1. Relation of CM cell activity to static wrist torque

<table>
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<tr>
<th>Cell</th>
<th>Antidromic Response Type</th>
<th>Rate-Torque Slope, Impulses s^{-1}/10^5 dyn·cm</th>
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<td>SW 121-1</td>
<td>P/T</td>
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<td>4.6</td>
</tr>
<tr>
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<td>P/T</td>
<td>*</td>
<td>4.4</td>
</tr>
<tr>
<td>SW 108-8</td>
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</tr>
<tr>
<td>SW 124-1</td>
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<td>*</td>
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</tr>
<tr>
<td>SW 117-3</td>
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</tr>
<tr>
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<tr>
<td>SW 108-1</td>
<td>P/R</td>
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<td>3.8</td>
</tr>
<tr>
<td>SW 110-2</td>
<td>P/R</td>
<td>*</td>
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</tr>
<tr>
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<tr>
<td><strong>Flexion cell</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SW 100-1</td>
<td>P/T</td>
<td>1.1</td>
<td>1.6</td>
</tr>
</tbody>
</table>

* Cells are identified by monkey and track number. The type of response pattern during ramp-and-hold wrist movements is indicated as P/T, phasic tonic; T, tonic; P/R, phasic-ramp; R, ramp. The latency of antidromic response to PT stimulation is given in milliseconds. The rate-torque slope gives slope of linear portion of curves of tonic firing rate versus static torque, in impulses s^{-1}/10^5 dyn·cm. * Not tested.

The discharge of some precentral cortex neurons has been found to be more related to the rate of change of torque (dT/dt) than to static torque for isometric (12, 24) and isotonic (5, 14) responses; with wrist movements against elastic loads (similar to ours), Schmidt et al. (22) found little evidence that the torque derivative was coded in phasic activity of precentral cells. While the response patterns of our tonic and ramp CM cells appeared primarily related to static torque, the phasic cells showed a peak at onset that could be compared with the rate of change of torque. Since the dynamic phases of wrist movements against different loads were generally executed in about the same time, the derivative of torque usually varied as a function of load (while wrist velocity remained approximately constant). The range of dT/dt for 13 phasic-tonic and three phasic-ramp CM cells was adequate to analyze their relation to this parameter of movement. To estimate the neurons' dynamic response, we measured the dynamic index, i.e., the peak frequency minus the tonic rate 0.5 s after reaching the plateau (cf. Ref. 17). The dynamic index of all 3 phasic-ramp cells and 5 of 13 phasic-tonic
cells increased with $dT/dt$; for 2 cells it decreased. The relation to $dT/dt$ in the absence of changes in position was confirmed for three cells studied under isometric conditions.

**Comparison of CM cell activity during ballistic and ramp movements**

One monkey periodically expressed frustration with the requirements of the task by performing ballistic wrist movements alternating rapidly between flexion and extension. The responses of six CM cells recorded during such ballistic movements were compared with their responses during more carefully controlled ramp-and-hold movements. None of the six exhibited appreciable activity during the ballistic responses. For three cells this was consistent with their activity during ramp-and-hold movements since these cells became active only after the final wrist position was attained. However, the other three cells, which reliably showed substantial activity at onset of ramp-and-hold movements, became virtually inactive during ballistic movements. Two examples are illustrated in Fig. 10. Both were cells that became active before their target muscles. During ballistic movements, however, both CM cells were nearly inactive, despite the greater EMG activity in their target muscles and the greater wrist displacements. Based on their responses during ramp-and-hold movements, at least 5 spikes would have been expected from cell SI 125-1 and 10 from cell SI 121-31 during the extension phase of the ballistic movement; instead, they were relatively inactive.

**Discussion**

**Functional classes of CM cells**

Investigations of precentral motor cortex cells during controlled limb movement have revealed a great diversity of response patterns, a wide range of onset latencies
Prior to movement, and differing degrees of relation to movement parameters. Some of this variability probably derives from sampling diverse types of precentral cells, with different projections. Using STAs to identify those motor cortex cells that produce output effects on forelimb motoneurons, we reexamined these issues for CM cells, identified by a characteristic PSF of motor-unit firing probability (8, 9). Since this PSF represents the mean effect of individual action potentials of a CM cell on its target muscles, the net effect of its activity during controlled wrist movements would be a muscle facilitation proportional to its firing rate.

On the basis of their phasic and tonic firing patterns during ramp-and-hold torque responses, all CM cells could be classified into one of four types. All discharged during the static hold, either at a constant rate (tonic cells) or gradually increasing rates (ramp cells). Some cells of each group exhibited clear phasic responses at onset of movement, greater than their subsequent tonic activity (phasic cells), while others showed no such phasic response. Response patterns of most CM cells fell clearly into one of these four classes, although some were intermediate. By far the most common response pattern was phasic-tonic, as found also by Smith et al. (24) for

FIG. 9. Relation between tonic firing rate and static torque for one CM cell during auxotonic responses and isometric responses made at three different wrist positions (0°, 25° extended, and 25° flexed). All points were measured from response averages of 25 events or more; firing rates and torques were measured 0.5 s after the end of the torque ramp. The isometric activity represents only that required to produce active torque since the internal load was subtracted by adjusting the resting torque to zero at each wrist position.
FUNCTIONAL CLASSES OF CM CELLS

precentral cells during performance of isotonic precision grip responses. The phasic activity of some phasic-tonic cells, although significant, was relatively weak; by the criteria of Smith et al., such cells might have been placed in their tonic category. In the present study only cells with response patterns showing no rapid adaptation or discontinuity near the end of the dynamic phase of movement were classified as tonic. Phasic-ramp and ramp cells were less common, but did represent distinct categories of CM cells. Similar ramp response patterns of unidentified precentral cells were described by Conrad et al. (3), who also observed them infrequently. The phasic-ramp pattern apparently has not been previously described for precentral cells. Their gradually increasing discharge during the static hold period may function to compensate for adaptation of motoneuron firing.

These four response patterns adequately describe the behavior of all CM cells encountered in this study of wrist movements against loads. Responses of many non-CM cells also fit well into these categories. Another response pattern encountered quite frequently in precentral cells that did not produce PSF is a purely phasic burst at movement onset. Phasically active cells usually had negligible spontaneous activity and fired briefly during the dynamic phase of movement, regardless of the magnitude of load opposing movement (cf. Ref. 22). Some of these cells were active for movement in only one direction; others fired with both flexion and extension. Such phasic cells were often encountered in regions surrounding CM cells. Their role in movement remains less clear, but does not appear to involve any direct link to motoneurons of the tonically active agonists.

The existence of CM cells with a distinct phasic component (phasic tonic and phasic-ramp types) and others with none (tonic and ramp types) during the same ramp-and-hold movement raises the possibility of different neural mechanisms for the dynamic and static activity. The phasic response does not appear to represent a different postsynaptic response to the same input that drives the tonic cells, since it consistently precedes such input. It seems more likely that CM cells are subject to two types of input, one related to the dynamic phase of
movement, the other to the steady-state component. The phasic-tonic cells would receive both types of inputs, while tonic cells receive only the static input. Since the phasic response begins before onset of agonist muscle activity, it must originate centrally; in contrast, the later tonic activity may include feedback from peripheral receptors. Most CM cells responded to passive joint movements that stretch their target muscles; if they receive input from stretch receptors in the muscles they facilitate, their steady-state discharge in the hold period could involve a peripheral feedback loop through their target muscles. Regarding possible interconnections between the observed cell types consistent with their firing patterns, it seems possible that phasic-tonic cells may receive input from phasic cells (non-CM) and from tonic cells; however, tonic cells could not receive any effective input from cells with phasic discharge.

**Onset times of CM cell activity**

Previous studies of onset times of precentral cell activity relative to onset of movement have consistently found a wide range of recruitment times, typically extending over several hundred milliseconds (7, 10, 20, 26, 27). The extensive overlap of distributions of onset times of unidentified cells in different regions (26, 27) have made it difficult to resolve the issue of their relative recruitment order without knowing more about their connectivity. In this study, the onset times of CM cells were measured relative to onset of their facilitated target muscles. CM cells exhibited a remarkably broad distribution of relative recruitment times, extending up to 120 ms before their target muscles. Since the mean latency of the PSF peak was 10.2 ms (9), the earlier CM cell activity probably exerted a subthreshold effect on motoneurons before their activation; such subthreshold facilitation has been confirmed by excitability testing (1).

The onset times of phasic cells were significantly earlier than onset of discharge in tonic or ramp cells (Fig. 3). Onset of phasic-tonic and phasic-ramp cells were not significantly different, as might be expected if their phasic activity had a common origin.

**Correlation of CM cell activity with force**

Since motor unit activity generates a proportional amount of contractile force and since some motor cortex cells affect motor-unit activity, the relation between activity of motor cortex cells and net force has attracted considerable experimental interest. In monkeys moving a handle through the same displacement against different weights (5) or generating different isometric forces (6), Evarts noted that PTN discharge was more strongly related to force or its temporal derivative than to wrist displacement. Similarly, Humphrey et al. (14) found activity of groups of precentral cells to be somewhat better correlated with torque trajectories than position or velocity; however, they found steady torque levels to be less easily predicted than dynamic trajectories. More recent studies have further confirmed the existence of some precentral cells clearly related to force and many others less well related (3, 12, 22, 24, 27). Again, some of this diversity may derive from sampling a heterogeneous population of neurons, including PTNs influencing non-agonist muscles and cortical cells without any descending projections.

In the present experiments CM cells, which facilitate activity of forearm muscles, had tonic discharge frequencies that increased monotonically with the static wrist torque produced by their target muscles over the entire torque range; in fact, their firing rate increased linearly with torque over part of this range. Since this activity facilitates target muscles proportionately, these CM cells would contribute causally to generating active force. The dynamic response of some phasic-tonic CM cells appeared to be related to rate of change of torque, but this was a less consistent finding than the relation between tonic activity and static torque. Nevertheless, a few cells showed a clear correlation with $dT/dt$ during isometric performance in which wrist movement and inertial loads were absent.

The rate-torque slope—the increase in mean firing rate per increase in static torque over the linear range—was relatively consistent within the flexion group and the
extension group of CM cells (Table 1, Figs. 5, 7, 8); the average torque slope was twice as great for extension CM cells (4.8 impulses/s/10^6 dyn cm) as for flexion cells (2.5 impulses/s/10^6 dyn cm). In other words, an increase of 1 impulse/s was associated with an increase in static torque of 4.2 x 10^{-6} dyn cm for flexion cells, and 2.1 x 10^{-6} dyn cm for extension cells. This unexpected difference may be related to a greater mechanical advantage for flexion than for extension. The hand was firmly clamped between padded plates to distribute the forces over the entire surface of contact; nevertheless, if the flexions were exerted via the finger tips while extension forces were exerted by knuckles, the greater radius of the former from the wrist could generate greater torques for the same muscle force (torque = force x radius). Differences in the distance from the wrist to points of insertion of flexor and extensor muscle tendons might also have given flexion movements a greater mechanical advantage. Such differences are difficult to quantify. When stimulated directly with the arm and hand positioned as during recording, extensor and flexor muscles produced comparable twitch torque responses.

Differences in the torque relation of flexion and extension PTNs were also evident in the wrist movement data of Evarts (5). Calculating from data in his Table 2 (including only cells that exhibited clearly greater activity in one movement direction than the other), we find that 14 extension cells had a mean torque slope of 86 impulses/kg, whereas six flexion cells had a mean slope of 51 impulses/kg. Similarly, in a later study involving isometric force (6), the five extension PTNs had a mean torque slope (41 impulses/kg) greater than the four flexion PTNs (34 impulses/kg). It is significant that these differences between flexion and extension PTNs are in the same direction as our results, even though the mechanics of the wrist movement differed substantially. In Evarts' study, the monkeys grasped a vertical bar by closing their fingers around it; in our experiments, the hand was held with fingers extended to separate flexor and extensor muscle activity. Moreover, Evarts' load was isotonic—i.e., constant in magnitude and direction, independent of displacement—while ours was auxotonic—proportional to and opposing displacement. The similarity in results suggests that the differences in the torque relation of the flexion and extension cells are not mediated entirely by external mechanical factors. The difference in rate-torque slopes may reflect differences in the cortical effects on flexor and extensor muscles. Clinical experience indicates that cerebral strokes generally produce greater paresis in wrist extensor muscles than in flexors. Intracellular studies have also revealed larger CM excitatory postsynaptic potentials (EPSPs) in motoneurons of EDC than motoneurons of flexor muscles (2). Similarly, in our experiments the strength of PSF was generally greater in extensor muscles than in flexors (9). Taken together, these results suggest that precentral cortex cells contribute a greater proportion of the descending input to extensor motoneurons; the fact that an increment in firing rate of flexion CM cells is associated with a greater increase in static torque may be due to a greater contribution to flexor motoneurons from other descending systems.

With regard to possible recruitment of CM cells with torque, only a few showed any appreciable torque threshold for tonic firing. This does not preclude the possibility that such recruitment might be more evident in monkeys specifically trained to generate very minute levels of EMG activity in wrist or digit muscles (11, 25). However, the direct cortical contribution to increases in torque over nearly its full range appears to be mediated more by increases in firing rate of the relevant CM cells than recruitment of additional CM cells.

Isometric responses

Quantitative interpretation of auxotonic responses is complicated by the fact that changes in torque are accompanied by changes in wrist position. Although wrist displacement was essentially the same for each level of active torque, it could contribute to cell activity. To separate these variables better, the activity of 10 CM cells was documented under isometric conditions in which ramp-and-hold torque trajectories were similar to those during auxotonic
responses, but wrist position was fixed. The response patterns and torque slopes of cells under isometric and auxotonic conditions were similar, confirming that torque was the significant correlated parameter. All four types of CM cell response patterns were observed under isometric conditions, with the phasic components undiminished in prominence. Hence, movement of the wrist appears to have a negligible role in the generation of the dynamic features of unit activity.

For some cells the isometric torque relation was documented at different wrist positions. Although the rate-torque slope did not vary consistently with position for all cells, for a given static torque the tonic firing rates of all but one CM cell were greater when their target muscles were shorter; i.e., the activity of these cells appeared to be adjusted in accordance with the length-tension properties of muscle. Although the length-tension relations have not been quantified for primate forelimb muscles, one would expect that the same wrist extension torque could be produced by less input to the relevant extensor motoneurons with the wrist flexed 25° than with it extended 25°. Extensor muscle spindle afferents would also contribute more to the excitability of homonymous motoneurons with the wrist flexed than extended.

Paradoxical responses of some CM cells during rapid movements

In the present study the response of some CM cells seemed to be paradoxically weak during rapidly alternating ballistic movements, compared with their activity during ramp-and-hold movements with similar velocities and EMG activity. This difference may be relevant to the hypothesis that different neural mechanisms are involved in generating fast and slow movements (4, 15). Conduction of peripheral input to motor cortex cells may also be less effective during ballistic than controlled movements (11). Afferent input to CM cells may contribute more to their activity during ramp-and-hold movements than rapid ballistic responses. Another possibility is that fast and slow motor units may be involved differently in these two types of movements. This would require separate pathways for activating them, with the relevant supraspinal cells being preferentially involved in fast or slow movements.

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REFERENCES


