# RESEARCH ARTICLE

Masato Taira · Jyl Boline · Nikolaos Smyrnis Apostolos P. Georgopoulos · James Ashe

# On the relations between single cell activity in the motor cortex and the direction and magnitude of three-dimensional static isometric force

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Abstract We examined the relations between the steady-state frequency of discharge of cells in the arm area of the motor cortex of the monkey and the direction and magnitude of the three-dimensional static force exerted by the arm on an isometric manipulandum. Data were analyzed from two monkeys (n=188 cells) using stepwise multiple linear regression. In 154 of 188 (81.9%) cells the regression model was statistically significant (P<0.05). In 121 of 154 (78.6%) cells the direction but not the magnitude of force had a statistically significant effect on cell activity; in 11 of 154 (7.1%) cells only the magnitude effect was significant; and in 22 of 154 (14.3%) cells both the direction and magnitude effects were significant. The same analysis was used to assess the effect of the direction and magnitude of force on the electromyographic activity of 9 muscles of the arm and shoulder girdle. The regression model was statistically significant. For all the muscles studied in 4 of 9 (44.4%) muscles only the direction effect was significant whereas in the remaining 5 of 9 (55.6%) muscles both the direction and the magnitude were significant. No muscle studied showed a significant effect of force magnitude alone. These differences in the frequency of occurrence of directional and magnitude effects between cells and muscles were statistically significant (P < 0.005,  $\chi^2$  test). These findings underscore the fundamental importance of the direction of force in space for both motor cortical cells and proximal muscles and underline the

M. Taira<sup>1</sup> · J. Boline · N. Smyrnis<sup>2</sup> · A.P. Georgopoulos J. Ashe  $(\boxtimes)$ 

Brain Sciences Center, Veterans Affairs Medical Center, One Veterans Drive, Minneapolis, MN 55417, USA

M. Taira · J. Boline · N. Smyrnis · A.P. Georgopoulos · J. Ashe Departments of Physiology and Neurology, University of Minnesota Medical School, Minneapolis, MN 55455, USA differential relations of the cells and muscles to the direction and magnitude of force. These results indicate that the specification of the magnitude of three-dimensional force is embedded within the directional signal; this combined direction+magnitude effect was 3.9 times more prevalent in the muscles than in the cells studied. In contrast, the pure directional effect was 1.8 times more prevalent in the cells than in the muscles studied. This suggests that the direction of force can be controlled independently of its magnitude and that this direction signal is especially prominent in the motor cortex.

**Key words** Motor cortex · Isometric force · Static force · Three-dimensional force · Monkey

# Introduction

The investigation of the relations of motor cortical cell activity to the force exerted began with the initial experiments on behaving monkeys by Evarts (1968, 1969). In the original and later work of Evarts and his colleagues (Evarts 1968; Evarts et al. 1983), and in subsequent work by others (e.g., Thach 1978; Cheney and Fetz 1980), the force exerted by the animal was restricted to one joint and to the activation of reciprocal groups of muscles, or to the thumb/index finger axis in studies involving a precision grip (e.g., Hepp-Reymond et al. 1978). In those experiments the activity of motor cortical cells varied with the magnitude of static force. In contrast, similar relations to force were not prominent for cells projecting to the striatum (Bauswein et al. 1989). The investigation of the neural relations to static force was extended to the direction of multi-joint, two-dimensional (2D) forces (Kalaska and Hyde 1985; Kalaska et al. 1989). It was found that cell activity in the motor cortex varied with, and was broadly turned to, the direction of force.

In spite of these studies, several questions remain unanswered. For example, there have been no studies of the effect of the magnitude of force on cell activity when

Present addresses:

 <sup>&</sup>lt;sup>1</sup> Department of Physiology I, Nihon University Medical School, 30-1 Ohyaguchi-kamikachi, Itabashi, Tokyo 173, Japan
<sup>2</sup> Department of Psychiatry, University of Athens Medical School, Aeginiteion Hospital, Ilisia, Athens, Greece

forces are exerted in the natural three-dimensional (3D) domain. Specifically, in the studies by Kalaska and collaborators (Kalaska and Hyde 1985; Kalaska et al. 1989) the magnitude of force was not varied, and, conversely, in all the other studies mentioned above the direction of force was not varied beyond a single axis. Therefore, a major question is: What is the relative contribution to cell activity of the magnitude and direction of static force? Is magnitude or direction more important for cell activity? Another question concerns the possible independence of these factors: Do magnitude and direction influence cell activity independently or are their effects coupled? Are there clear cases of magnitude effects that are independent of directional effects, and vice versa? And if so, what is the relative frequency of occurrence of these effects?

Obviously, static maintenance of force is a very limited aspect of the motor repertoire of the arm. In fact, all meaningful actions for the acquisition of objects of interest or for the avoidance of threatening objects involve movements, that is changes in force and posture. There is clear evidence that static and dynamic factors do not always have congruent effects on cortical cell activity (Georgopoulos and Massey 1985), and that when a purely dynamic change in isometric force is generated, motor cortical cell activity reflects the dynamic and not the static component of the force exerted (Georgopoulos et al. 1992). Therefore, there appear to be two separate processes that influence motor cortical cell activity, namely a static and a dynamic process (Ashe et al. 1994). As a first step in studying the neural mechanisms of these processes, this paper deals with the static force effects in motor cortex. Unlike previous studies mentioned above, the isometric force that the animals exerted varied in 3D force space, since force is naturally at 3D vector, as well as in magnitude. Thus we attempted to provide a bridge to previous research but also to evaluate quantitatively the perennial question of the effects of magnitude and direction of 3D force on motor cortical cell activity when both of these parameters were allowed to vary.

## **Materials and methods**

## Animals

Two male rhesus monkeys (*Macaca mulatta*, 3.5–5 kg body weight) were used. Care and treatment of the animals during all stages of the experiment conformed to the principles outlined in *Principles of Laboratory Animal Care* (NIH publication no. 86-23, revised 1995).

## Apparatus

A 3D isometric manipulandum and a video monitor were used in the task. The manipulandum has been described previously (Massey et al. 1988). Briefly, it was a vertical rigid metal rod with a disc attached to the top. The manipulandum was placed in front of the animal in the midsagittal plane and was grasped by the animal with the hand pronated. The rod was 7.8 cm long and was mounted vertically and perpendicular to the plane of three load cells. Force exerted on the disc was read with a resolution of 0.004 kilogram force (kgf; 0.039 N) and a precision of  $\pm 0.004$  kgf (0.039 N). The conventions for the orientation of the positive axes of the coordinates of the force vector were as follows: the X axis pointed to the left of the animal, the Y axis pointed towards the animal, and the Z axis pointed downward.

The video monitor was placed at eye level 45 cm in front of the animal. The display was high-definition gray scale. It was used to instruct the animal on the direction and magnitude of force in XY dimensions and to provide visual feedback of the force exerted through a force-feedback cursor. The application of 0.010 kgf (0.098 N) on the manipulandum in the X or Y direction caused a movement of 3.75 mm of the force-feedback cursor in the same direction on the screen.

## Behavioral task

The task was visually instructed in the XY force space but forces were measured in XYZ dimensions. A steady deflection of the force-feedback cursor was used to produce a simulated constant bias force in eight directions equally separated (every 45°) within the XY force space. The deflection placed the cursor on a circle of 0.045 kgf (0.441 N) or 0.18 kgf (1.76 N) radius, for the first and second monkey, respectively. At the beginning of each trial, the visual target first appeared in the center of the display and the animal had to exert a constant force on the manipulandum in a direction opposite to the bias force to align the force-feedback cursor to the center target within a circle of 0.02 kgf (0.196 N) radius. This constant force had to be maintained by the animal for 0.8 to 1.2 s "center hold period") after which the visual target jumped to a peripheral location on the screen and triggered a force pulse by the animal (Georgopoulos et al. 1992). In the present paper we consider only the static force exerted during the last 0.3 s of the center hold period (see "Data analysis" below). For each cell 192 trials were used (8 bias forces  $\times$  24 repetitions). The bias forces were presented in a randomized sequence, and all repetitions were done in successive trials within each bias. The inter-trial interval was 1.5–2 s.

#### Neural recordings

After the animals had been trained and performed with greater than 85% accuracy in the task, we began extracellular recordings in the motor cortex during task performance using a seven microelectrode recording system (Mountcastle et al. 1991). The electrophysiological techniques used to record the electrical signs of single cell activity, the surgical procedures and the animal care have been described previously (Georgopoulos et al. 1982; Lurito et al. 1991). In the present experiments we used a lightweight metal halo (Nakasawa Works Co., Tokyo) to stabilize the head during recording sessions. Neural impulses were discriminated on line using dual time-amplitude window discriminators (BAK Electronics, Md).

#### Electromyographic recordings

The electromyographic (EMG) activity was sampled during performance of the task using intramuscular, Teflon-coated, multistranded, stainless steel wires. The following proximal muscles were sampled: in the first monkey, anterior deltoid, posterior deltoid, upper trapezius, pectoralis, biceps, triceps; in the second monkey; anterior deltoid, posterior deltoid, upper trapezius, lower trapezius, pectoralis, supraspinatus, infraspinatus. The EMG recordings were made separately from neural recording sessions. The EMG signals were recorded differentially, amplified through a Grass amplifier system with an amplification of 10000–20000, bandpass filtered at 30–300 Hz, sampled at a rate of 1 kHz, and rectified. Fig. 1 Schematic diagram to illustrate the calculation of counts of fractional interspike intervals in a binned time period. *Numbers* underneath intervals indicate fractions; whole intervals=1.0, whereas intervals separated by the *lines* demarcating the time bin are split into fractions. The numbers of fractional intervals is the sum of the whole intervals plus the fractions inside the lines of demarcation



#### Anatomy

At the end of the experiment the area of recording was demarcated on the cortical surface using pins inserted into the cortex at known locations. Then the animals were killed using a large dose of sodium pentobarbital, perfused transcardially with buffered formalin, and the brain removed.

#### Data collection

A personal computer was used to control and implement the task, to monitor the behavior of the animal and to store the neural and EMG data. The output of the manipulandum in XYZ dimensions was sampled every 5 ms. Neural data were collected as interspike intervals with a resolution of 0.1 ms.

#### Data analysis

All analyses for the present studies were done for data recorded during the last 0.3 s of the center hold period ("static force period") in each of 192 trials (see above). The force data consisted of the average XYZ components of the force exerted during that period (n=60 time samples, every 5 ms). The neural data were rates of cell discharge (impulses/s) computed from counts of fractional interspike intervals (Fig. 1) during the static force period. This is a more accurate measure of binned neuronal activity because the period of interest is regarded as part of the spike train within which it is embedded. Analyses were also performed using rates of cell discharge calculated from simple counts of spikes during the static force period above. Finally, EMG data consisted of the average EMG activity (arbitrary units) recorded during that period (n=300time samples, every 1 ms).

Standard analysis (Draper and Smith 1981; Snedecor and Cochran 1989) and display techniques were used to inspect, evaluate and analyze the data. Methods for analyzing directional data (Mardia 1972; Fisher et al. 1987) were also used when appropriate. A level of P<0.05 (two-tailed) was regarded as statistically significant in all tests performed.

#### The three-dimensional force space

The purpose of this study was to determine the relations between single cell activity and the direction and magnitude of 3D static isometric force. Let F be a 3D force vector and  $F_x$ ,  $F_y$ ,  $F_z$  its XYZ components:

$$\boldsymbol{F} = [F_x, F_y, F_z] \tag{1}$$

The magnitude *M* of *F* is a scalar equal to the length of vector *F*:

 $M = |F| = (F_x^2 + F_y^2 + F_z^2)^{\frac{1}{2}}$ 

The direction of F is the set of its direction cosines (Mardia 1972), that is the cosines x, y, z of the angles  $\delta$ ,  $\xi$ ,  $\eta$  that F makes with the positive XYZ axes, respectively:

$$x = \cos(\delta), \quad y = \cos(\xi), \quad z = \cos(\eta)$$
 (3)

The direction cosines were computed as follows:

$$x = F_x / M, \quad y = F_y / M, \quad z = F_z / M \tag{4}$$

#### Stepwise multiple linear regression

The program 2R of the commercially available package BMDP Statistical Software Inc., Los Angeles, Calif., 1993) was used to perform the stepwise multiple regression. The dependent variable was the frequency of cell discharge. There were two sets of independent (predictor) variables: the force magnitude M and the direction cosines [x, y, z] of the force vector  $\vec{F}$ . The program fitted a multiple linear regression equation in a stepwise manner by entering or removing one variable at a time from the list of these two sets of independent variables; the direction cosines were entered as a set. Only forward stepping was used, i.e., beginning with no predictors. The default values (for the program) of the  $\tilde{F}$  statistic to enter or remove a predictor in a step were used (F-to-enter=Fto-remove=4.0). The default tolerance level of 0.01 was used which provided a check and safeguard against possible collinearity effects. After stepping, the following final outcomes were possible: (a) Neither of the two sets of predictors had a significant effect; in this case there was no significant regression model. (b) At least one set of the predictor variables had a significant effect; in this case there was a statistically significant regression model. More specifically, if only the directional effect was significant, this indicated a purely directional effect, if only the magnitude effect was significant, this indicated a purely magnitude effect; and if both the directional and magnitude effects were significant, this indicated a combined direction+magnitude effect.

The equation for the purely directional model was:

$$d=b_0+b_x x+b_y y+b_z z+e \tag{5}$$

where d is the frequency of discharge,  $b_0$  is the intercept,  $b_x-b_z$  are partial regression coefficients for the variables above, and e is an error term. This equation can be reexpressed as follows (see Schwartz et al. 1988 for details):

$$b_x x + b_y y + b_z z = h \cos\theta_{JF} \tag{6}$$

where

(2)

$$h = (b_x^2 + b_y^2 + b_z^2)^{\frac{1}{2}}$$
(7)

$$\boldsymbol{J} = [\boldsymbol{j}_x, \boldsymbol{j}_y, \boldsymbol{j}_z] \tag{8}$$

$$j_x = b_x/h, \quad j_y = b_y/h, \quad j_z = b_z/h$$
 (9)

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and  $\theta_{JF}$  is the angle between the force vectors J and F. J is the *preferred force direction*, that is the direction of force in which cell activity is maximum. Therefore the regression model in Eq. 5 can be reexpressed as follows:

$$d=b_0+h\cos\theta_{IF}+e\tag{10}$$

The equation for the purely magnitude model was:

$$d=b_0+b_m M+e \tag{11}$$

where  $b_m$  is a regression coefficient.

Finally, the equation for the combined direction+magnitude model was:

$$d=b_0+b_x x+b_y y+b_z z+b_m M+e$$
(12)

or, equivalently,

 $d=b_0+h\cos\theta_{IF}+b_m\,M+e\tag{13}$ 

The same analysis as above was performed on the EMG activity.

# Results

## General

We recorded the impulse activity of 188 cells in the arm area of the motor cortex (two hemispheres, two animals) during performance of the task described above. Each cell changed activity in relation to proximal movements of the contralateral arm, as judged by examination of the animal outside the behavioral task. No cells activated with distal (hand or finger) movements or with passive driving from the hand or fingers are included in this sample.

## Behavioral performance

Altogether, 36096 successful trials were performed (188 cells  $\times$  8 force biases  $\times$  24 repetitions). All forces con-

Fig. 2 Neural activity of a motor cortical cell during exertion of 3D static force. In the scatter diagram the observed discharge rate is plotted against the discharge rate predicted by the following regression model: d=28.8-20.1 x-2.0 y-15.1 z $(R^2=0.733, P<0.00005, n=192)$ trials). The impulse activity during the 300-ms static force period (see Methods) is shown in the *left-hand panel* and is rank-ordered from lowest to highest discharge rate, corresponding to the scale in the ordinate (n=192 trials). [Cell: Rho007(7)]



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sidered in this paper were static (see Methods). The ranges of the forces exerted were as follows:  $F_x$ , -0.219 to 0.231 kgf, median=0.0035 kgf (-2.146 to 2.361 N, median 0.034 N);  $F_y$ , -0.227 to 0.241 kgf, median=0.0002 kgf (-2.225 to 2.362 N, median=0.002 N);  $F_z$ , -0.211 to 0.463 kgf, median=0.0036 kgf (-2.067 N to 4.537 N, Median=0.035 N). The range for *M* was 0.026 to 0.499 kgf, median=0.059 kgf (0.255 to 4.890 N, median=0.578 N). Finally, the pairwise correlation coefficients between the *xyz* directions of the forces exerted were as follows: *x* vs y, *r*=0.0109; *x* vs *z*, *r*=0.0105; and *y* vs *z*, *r*=-0.1626.

Quantitative relations to three-dimensional force

Of the 188 cells studied, 154 (81.9%) showed a significant multiple regression model, whereas for the remaining 18.1% of the cells the model was not significant. A purely directional model was obtained in 121 of 154 (78.7%) cells; an example is illustrated in Figs. 2 and 3. A purely magnitude model was obtained in 11 of 154 (7.1%) cells, and a combined direction+magnitude model was obtained in 22 of 154 (14.3%) cells. Therefore, a total of 143 cells showed a significant directional effect. The preferred directions of these cells are plotted in Fig. 4. The null hypothesis that preferred directions were uniformly distributed was tested for each of the two monkeys and for both groups of directionally tuned cells, namely with and without a magnitude effect. In all cases the null hypothesis was not rejected (Rayleigh test; Mardia 1972).

Very similar results were obtained when the spike counts were used instead of the counts of fractional intervals. (The correlation between counts of fractional intervals and counts of spikes was very high: r=0.995, P<0.00005, n=36096 trials).

40 40 20 20 10 0 0 10 0 10 0 10 20 30 40 50 60 70

Predicted (imp/sec)

Fig. 3 Normal cumulative probability-probability plot (*thick line*) of the observed regression residuals against those expected from a normal distribution. The *thin line* along the diagonal indicates the case for a perfect normal distribution. Data are from the cell illustrated in Fig. 2



Fig. 4 Distribution of preferred force directions (unit length vectors) in 3D for all cells with significant directional effect (n=143)

**Fig. 4** Distribution of preferred force directions (unit length vectors) in 3D for all cells with significant directional effect (n=143). 3D The mean resultant was 0.0996; null hypothesis of uniform distribution not rejected (P>0.2, Rayleigh test; see Mardia 1972). Data were right-hand converted P < 0

Expected Cumulative Probability

Fig. 5 EMG activity of right pectoralis muscle during exertion of 3D static force. The observed activity (arbitrary units) is plotted against the activity predicted by the following regression model:  $a=0.274+1.006 \ x-0.003 \ y+0.701 \ z-2.022 \ M \ (R^2=0.875, P<0.00005, n=192 \text{ trials})$ 

# EMG activity

Z-axis

Many different muscles contributed with varying levels of activity to the production of any particular static force vector. Conversely, the activity of individual muscles varied with force exerted. The same analyses as above were used to assess the effect of the direction and magnitude of force on the EMG activity of 9 muscles of the arm and shoulder girdle. For all these muscles the regression model was statistically significant. In 4 of 9 (44.4%)



Fig. 7 The sites from which neural activity was recorded outlined on two hemispheres from the two animals used in the study. All recordings were within the motor cortex. CS central sulcus, AS arcuate sulcus

As described above, the frequency of occurrence of direction and magnitude effects differed between the cells and muscles studied. These differences were statistically significant (P<0.005,  $\chi^2$  test).

muscles (anterior deltoid, upper trapezius, infraspinatus, triceps) only the direction effect was significant, whereas in the remaining 5 (55.6%) muscles (posterior deltoid, pectoralis, biceps, lower trapezius, supraspinatus) both the direction and the magnitude were significant. An example is illustrated in Figs. 5 and 6. No muscle studied showed a significant effect of force magnitude alone. Some muscles were studied in both monkeys (anterior deltoid, posterior deltoid, upper trapezius and pectoralis). The same effects of direction and magnitude of force were observed for these muscles in both monkeys.

## Anatomy

The neural recordings in the isometric task were made in two hemispheres of two animals. All electrode penetrations were within the motor cortex (Fig. 7).

# Discussion

Despite almost three decades of study, our understanding of the relations of motor cortical cell activity to static

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force exerted remains incomplete. The reason is that these relations have commonly been investigated only within restricted domains of the 3D force vector, namely with respect to its magnitude in only one dimension (see Evarts 1981) or with respect to its direction in only two dimensions and the magnitude fixed (Kalaska and Hyde 1985; Kalaska et al. 1989). To our knowledge, this is the first study of the relations between motor cortical cell activity and static force in three dimensions, and also the first in which both the direction and the magnitude of the force were allowed to vary. The principal findings of the study were as follows: (i) the activity of a majority of cells was best related purely to the direction of force, (ii) the activity of a small number of cells was related exclusively to the magnitude of force, and (iii) the activity of an intermediate number of cells was related to both the direction and the magnitude. We discuss these points separately below.

## Methodological considerations

Although the study of visually guided arm movements in 3D space is methodologically feasible and practically relatively easy, the study of visually guided 3D isometric force is fraught with methodological difficulties. The main problem is that the three-dimensionality of the force vector, although obvious, is very difficult to instruct visually. The difficulty lies in the design of an adequate 3D display. An attempt to instruct human subjects to accurately produce 3D isometric forces specified by a target on a stereogram was relatively unsuccessful (Massey et al. 1990). In the present study, we adopted a practical alternative to the full 3D specification of isometric force, namely to instruct force on a plane, so that two force components were controlled, while all three components were measured during the task. Thus, the forces exerted in the X and Y dimensions were controlled to be, by design, at regular interval in the XY force space, while the force exerted in the Z dimension was allowed to vary. This design resulted in 3D forces which varied in both direction and magnitude.

## Magnitude of one-dimensional force

In studies of the relations between motor cortical cell activity and force, the magnitude and direction components of the force vector have traditionally been treated separately. Nevertheless, from the early work of Evarts (1968, 1969), it is the magnitude of force that has dominated the literature. Concerning the relations between motor cortical activity and the magnitude of static force, there have been a number of findings. The relation is generally monotonic (Evarts 1969; Smith et al. 1975; Thach 1978; Hepp-Reymond et al. 1978; Cheney and Fetz 1980; Evarts et al. 1983; Fromm 1983; Wannier et al. 1991; Maier et al. 1993) and this holds for different body parts and over a wide range of forces. In a proportion of cells the monotonic relation may only be evident over a restricted force range (Evarts et al. 1983; Hepp-Reymond et al. 1978; Werner et al. 1991). The rate of increase in cell activity per unit increase in the magnitude of static force can vary widely (Hoffman and Luschei 1980; Evarts et al. 1983; Wannier et al. 1991; Maier et al. 1993).

In the studies cited above it was virtually impossible to examine the relation between motor cortical cell activity and direction of force in any meaningful way because the force vector was restricted to one dimension. This limitation was the result either of an inherent biomechanical constraint of the joint, or of an external constraint imposed on a joint or joints with a potentially greater number of degrees of freedom, for example the wrist (Evarts 1969; Thach 1978; Cheney and Fetz 1980) and the various joints of the first and second digits in the precision grip (Smith et al. 1975; Hepp-Raymond et al. 1978; Wannier et al. 1991; Maier et al. 1993). In those studies, the design greatly influenced the results for the reasons outlined above, and led to the common belief that the relation between motor cortex and static force was synonymous with the relation to the *magnitude* of static force.

In the present study the activity of only a small proportion of cells (7%) was related to the magnitude of force alone. Therefore, within the more natural behavioral conditions in which both direction and magnitude of force are allowed to vary, the magnitude of force by itself seems to be a much less important determinant of cell activity than suggested by other studies. The coding of static force by the motor cortex can be best understood in the directional domain.

Direction of two-dimensional force

Kalaska and collaborators (Kalaska and Hyde 1985; Kalaska et al. 1989) were the first to examine the issue of the coding of the direction of 2D static force. In this experiment monkeys were required to hold a manipulandum in position while resisting forces of constant magnitude (0.083 kgf) that operated on the manipulandum in eight different directions in 2D. It was found that many cells (59.5%) were broadly tuned to the direction of force. This finding has led to the belief that static force is synonymous with *direction* of static force. For example, studies on the relative involvement of the motor cortex and parietal area 5 in the coding of force have concluded that area 5 relates little to specification of force output on the basis of lower modulation of cell activity in that area during the production of constant forces in different directions (Kalaska and Hyde 1985). However, it is possible that neurons in area 5 may have a strong relation to the magnitude of force, but this was not tested. Therefore, equating static force with its direction is as ungrounded as the earlier tendency to equate static force with its magnitude.

## Direction and magnitude of three-dimensional force

We regard both the direction and the magnitude of static force as potentially important determinants of motor cortical cell activity. Consequently, in the design of this study both were allowed to vary, and all three dimensions of the force vector were employed. The results obtained seem to justify our assumption that both direction and magnitude are of importance in that the effects of each could be separately identified in cell activity.

The number of cells whose activity related exclusively to magnitude, independent of direction, was small (7% of the cells that showed significant relation to the model). It could be argued that this small percentage could be due to the range of forces produced in the task (0.026-0.499 kgf; 0.255-4.890 N). This is not likely, however, as other studies have shown that cells have maximal sensitivity to force within that range (Evarts et al. 1983; Wannier et al. 1991; Maier et al. 1993) and that few cells are recruited at higher forces. Given the relatively small proportion of cells involved specifically with force magnitude at the level of the motor cortex, how then is the magnitude of force specified? One possibility is that these cells, even if small in number, have a disproportionate influence through their patterns of connectivity with other parts of the motor system. Another possibility is that other cortical areas may be involved in the specification of the magnitude of static force. For example, cells in area 5 have prominent sensory input from the primary somatosensory cortex (Jones and Powell 1969, 1970; Pandya and Kuypers 1969; Vogt and Pandya 1978) and show little modulation with direction of static force (Kalaska and Hyde 1985), but they could play a role in the coding of the magnitude of force. This remains to be tested.

In the present study the steady-state discharge rate of a great majority (78.6%) of cells was related to the direction of force alone. These cells were tuned to the direction of force and the distribution of their preferred directions was uniform. In previous studies of the relations of motor cortical activity to the direction of static force (Kalaska and Hyde 1985; Kalaska et al. 1989) the relations to static force magnitude were not tested. Therefore, it is not known whether the cells studied in those experiments were related to direction alone or to both the direction and the magnitude of force. The important point is that when both the direction and the magnitude of static force are allowed to vary concurrently, the effect of direction is still the predominant one. A relatively small percentage of cells were related to both direction and magnitude. Therefore, it would seem that in the motor cortex (i) the direction and magnitude of force are governed by two different processes subserved by different populations of cells, and (ii) the majority of force-related cells are involved in the specification of the direction of force.

In considering potential explanations for our findings we need to take into account different factors that have been shown to influence motor cortical cell activity. At

the most general level, the cell discharge rates we observed during the task could reflect both the role of the motor cortex in coding motor output (see Evarts 1981; Porter and Lemon 1993) and feedback from the periphery to the motor cortical cells (Wolpaw 1980). It is instructive to consider in greater detail the different efferent and afferent processes that may be engaged in the maintenance of static isometric force, any or all of which may be reflected in the activity of motor cortical cells. These processes involve different levels of the motor and somatosensory system from receptors in muscles and other structures to the motor cortex. For example, during isometric contraction there is coactivation of the alpha and fusimotor neurons to the muscles (Vallbo et al. 1979). This coactivation is tightly coupled in three respects: (i) in the spatial domain, as the fusimotor output is restricted to the contracting muscles (Vallbo 1970), (ii) in the temporal domain, as changes in alpha and fusimotor output seem to occur simultaneously (Vallbo 1971), and (iii) in the intensity domain, as there is a close relation between the intensity of spindle firing and the amount of torque exerted (Vallbo 1974). Although in primates the motor cortex can influence the motoneurons directly (Porter and Lemon 1993), in most cases the motor cortex addresses motoneurons via intercalated interneurons (Lundberg 1979; Kuypers 1981). During the activation of proximal arm muscles, specialized interneuronal systems, such as the propriospinal interneuronal system (Illert et al. 1977; Alstermark et al. 1981) and probably other systems (Baldissera et al. 1981), may be instrumental in translating neural activity in the motor cortex into appropriate patterns of muscle activation.

With regard to input from the periphery, information comes predominantly from two muscle receptors: the muscle spindle (primary and secondary endings) and the Golgi tendon organ. Spindle afferents are active during isometric contractions due to the fusimotor activation mentioned above. This input can reach the motor cortex at short latencies (Wolpaw 1980) through direct and indirect cortical routes (Oscarsson and Rosen 1963; Jones et al. 1979; Asamuma et al. 1980), and also via the cerebellum (Bloedel and Courville 1981). The Golgi tendon organ, which monitors muscle tension, is also active under isometric conditions; this information is transmitted to the cerebellum and possibly from there to the motor cortex (Bloedel and Courville 1981). Given the complexity of the afferent processes involved in the production and maintenance of static isometric force, and the number of different variables that may be reflected in motor cortical activity, it is remarkable that there is a lawful and relatively simple relation between cell activity and the direction of force exerted.

Relation of EMG activity to static force vector

There has been only one systematic study of the relations between EMG activity in proximal arm muscles and the direction and magnitude of static forces produced at the wrist (Flanders and Soechting 1990). In this study forces of three different magnitudes were applied to the wrist of human subjects in over 20 different directions within a plane. It was found that the relation between force direction and EMG amplitude could be best fitted using a multiple cosine tuning function; unimodal tuning was the exception. The amplitude of the muscle activity tended to scale with the magnitude of the force. In addition, the direction of peak EMG activity did not change significantly with different levels of force. Two general conclusions can be drawn from this work; namely (i) that processes governing the direction and magnitude of static isometric force have similar manifestations in EMG activity, and (ii) given the difference in tuning between the muscles and cells recorded during similar tasks, that "there does not appear to be a one-to-one relation between the discharge of cortical neurons and the activation of motoneurons" (Flanders and Soechting 1990). The results of the EMG recordings in the present study are consistent with both conclusions. The effects of the magnitude of force are not seen separately in muscle activity but are coupled with the effect of force direction. The proportions of cells and muscles relating to the direction and magnitude of the force differ: the vast majority of cells related exclusively to the direction of force, whereas the majority of the muscles related to both direction and magnitude; thus the behavior of the cells and that of the muscles is not exactly congruent.

#### Static force versus movement

The present study has to be viewed strictly within the context of static force. Although directional tuning has been demonstrated during movement in other studies (Georgopoulos et al. 1982; Schwartz et al. 1988), those results cannot legitimately be compared with the current work. To illustrate the potential difficulties in comparing isometric force and movement, it is worth considering the differences between these conditions in some detail. Firstly, static isometric force production is a steady state in which the force is kept constant, whereas during movement the force is continuously changing. Secondly, the definition of the forces in the isometric case is unequivocal while the definition of the forces during movement presents serious complications and potential problems. For example, during movement, does one consider the force exerted by the subject or the net force exerted by the arm? Should the interaction forces (Hollerbach and Flash 1982; Karst and Hasan 1991) be included? Thirdly, another obvious difference between the isometric and movement conditions is that in the first case the limb is fixed, whereas in the second case there is displacement. With displacement there is considerable activation of peripheral receptors associated with change in muscle length, joint angles, and the position of the limb and limb segments in space; all these variables remain constant in the isometric condition. Finally, there is a basic difference in the innervation of the muscles in the movement case, in which alpha and fusimotor neuron output are loosely coupled, versus the isometric case, in which the coupling is rigid (Vallbo 1974).

Comparisons between the current static isometric force study and other isometric force studies in which the force output was dynamic (Georgopoulos et al. 1992) also may not be easily interpretable for the following reasons. Static and dynamic force output may be mediated by different processes and the relations between cell activity and force may be quite different, depending on which process is predominant. For example, some general comparisons in the past between static posture and movement have shown substantial differences in the directional and spatial tuning for cells in the motor cortex and in area 5 (Georgopoulos and Massey 1985). When a particular motor behavior requires a mixture of static and dynamic forces to be produced, the separate processes govering the production of these forces may be reflected in the activity of single cells within the motor cortex (Ashe et al. 1994). The nature of the interaction between these processes and how this interaction is reflected in cell activity remains to be elucidated.

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