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FORELIMB ELECTROMYOGRAPHIC RESPONSES TO MOTOR CORTEX STIMULATION DURING LOCOMOTION IN THE CAT

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SUMMARY

1. The forelimb motor cortex was stimulated via chronically implanted micro-electrodes whilst electromyographic (e.m.g.) responses were recorded from muscles in the contralateral forelimb in cats walking steadily at 0·5 m/s. The stimuli were brief trains of 0·2 ms pulses (11 pulses at 330 Hz), intensity 5–20 μA and e.m.g.s were recorded from the following muscles: biceps brachii, brachialis, long and lateral heads of triceps brachii, latissimus dorsi, cleidobrachialis, extensor digitorum communis, palmaris longus and flexor and extensor carpi ulnaris.

2. During locomotion, stimulation at 20 μA readily elicited brief, short-latency changes in the normal locomotor patterns of activity in all muscles studied. The changes included production of e.m.g. at times in the step cycle when the muscles are normally inactive and brief augmentations or diminution of the normal locomotor e.m.g.s. Individual electrodes usually influenced several muscles, and muscles acting antagonistically about the same joint were sometimes co-contracted.

3. The first effect on locomotor flexor muscles (i.e. muscles active in relation to the swing phase of the step cycle) was almost always excitatory and such effects were often phase-dependent, usually occurring when the muscle was normally active or about to become active.

4. Extensor muscles were excited from some cortical loci but inhibited from others (inhibitions were necessarily detectable only when the muscles exhibited locomotor-related e.m.g.s). Some micro-electrodes elicited excitation during swing (when the extensors are inactive) but elicited inhibition during stance.

5. In several muscles the latencies of the excitatory e.m.g. changes could be as short as 6 ms measured from the first pulse in the stimulus train. In flexors, but not in extensors, latencies fluctuated according to the timing of the stimuli relative to the step cycle.

6. Reduction in stimulus intensity reduced the amplitude of the e.m.g. changes, the number of muscles influenced and often increased the latency. However, both excitations and inhibitions were sometimes evident at 5 μA and thresholds for excitatory responses were, over-all, substantially lower than in the resting animal.

7. Longer trains of stimuli were capable of resetting the step cycle.

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8. Response thresholds were greatly increased after pyramidectomy.

9. These findings support the view that the natural bursts of impulses discharged by pyramidal tract neurones during steady locomotion are likely to contribute to regulating forelimb muscle activity on a step-by-step basis.

INTRODUCTION

During locomotion large numbers of motor cortical neurones show marked modulations of their discharge frequency, which are phase-locked to the step cycle (Armstrong & Drew, 1984*a*, *b*). Many pyramidal tract neurones fire in a burst–silence–burst pattern with (usually) one burst per step and it seems *a priori* likely that such activity will play some role in generating or modulating the patterns of muscular activity which underlie the walking movements.

Nevertheless, it would be unwise to assume too readily a causal relationship between the discharges and the locomotion because in the cat at least one spinal interneurone is always interposed between the terminals of the corticospinal axons and the α-motoneurones (Lloyd, 1941; Lundberg & Voorhoeve, 1962; Illert, Lundberg & Tanaka, 1976). It is possible that during steady locomotion such interneurones are inhibited or disfacilitated and that corticospinal outputs are permitted to influence the α-motoneurones only when some marked adaptive change in gait is required.

This is not merely an academic possibility. The effects of intracortical microstimulation on muscles of the contralateral forelimb show considerable posture dependence even in the stationary animal, probably because of changes in the excitability of spinal motor mechanisms (Armstrong & Drew, 1985). Moreover, locomotion on a flat surface is only transiently impaired by pyramidectomy (Liddell & Phillips, 1944; Eidelberg & Yu, 1981) or by lesions of the motor cortex (Adkins, Cegnar & Rafuse, 1971).

To assess further the role of motor cortical activity in the control of steady locomotion we have therefore evoked cortical efferent discharges by intracortical stimulation via chronically implanted micro-electrodes in use to record from motor cortex neurones (Armstrong & Drew, 1984*a*, *b*). Brief trains of weak stimuli were delivered at different times during the step cycle whilst the animals walked at a speed of 0·5 m/s on a moving belt and effects of these stimuli were monitored electromyographically in muscles of the contralateral forelimb.

The results indicate that cortical stimulation during locomotion can produce powerful short-latency excitations of α-motoneurones supplying a variety of forelimb muscles and can also interrupt the natural locomotor activity in some muscles. Such effects are virtually abolished by pyramidectomy, suggesting they are mediated mainly via the corticospinal tract. We therefore suggest that the natural rhythmic discharges of pyramidal tract neurones very probably play a significant role in the neural control of steady locomotion at walking speed.

METHODS

Micro-electrodes were implanted into the right pericruciate cortex of five cats to record extracellularly from motor cortical neurones during locomotion (see Armstrong & Drew, 1984*a*). The electrodes were 17 μm diameter platinum–iridium microwires inserted to a depth of 1·5–2·0 mm

into the coronal gyrus and the lateral parts of the anterior and posterior sigmoid gyri at an initial aseptic operation using full barbiturate anaesthesia. Electromyography and intracortical microstimulation were carried out while the animals walked at a comfortable walking speed (0·5 m/s) on a moving belt (see Armstrong & Drew, 1984*a*). The animals were all adept at walking steadily to maintain constant position on the belt.

Electromyography

In each animal pairs of electromyographic (e.m.g.) leads were chronically implanted into a number of muscles in the left (i.e. contralateral) forelimb (see Armstrong & Drew, 1984*a*). Brachialis muscle and the lateral head of triceps brachii were always included. The other muscles varied between animals but collectively included cleidobrachialis, triceps brachii long head, biceps brachii, extensor digitorum communis, palmaris longus, latissimus dorsi and flexor and extensor carpi ulnaris muscles. Because some of these muscles are large the adequacy with which their activity was sampled was occasionally checked by inserting two pairs of leads into one muscle and comparing the recorded signals. In such cases the two e.m.g.s obtained during locomotion were similar in respect of both amplitude and timing. Any e.m.g. changes evoked by cortical stimulation were also similar.

A second control was also carried out to assess the extent to which recordings from one muscle might be contaminated by activity recorded at a distance and originating in other muscles. In two cats recordings of locomotor-related and cortically evoked activity were made from the elbow extensor lateral head of triceps brachii both before and after the muscle nerve was sectioned under full anaesthesia and with aseptic precautions. In both cases after nerve section no e.m.g. activity was detectable at the amplification normally used, indicating there was no significant pick-up either from the nearby elbow flexors (biceps brachii and brachialis) and/or from the adjacent long head of triceps which continued to yield e.m.g. activity.

Intracortical stimulation

Trains of 11 cathodal pulses at 330 Hz were employed (cf. Armstrong & Drew, 1984*c*, 1985). Pulse duration was 0·2 ms and intensity ranged between 5 and 20 μA, initial observations being made at 20 μA. The time of onset of the trains relative to the step cycle in the forelimb was controlled by converting the e.m.g. in brachialis muscle via a window discriminator into a train of standard pulses. The first pulse in each train was used to trigger the stimulator after a controllable delay ranging from 0 to 700 ms in 100 ms steps. Because brachialis is active for one brief period per step, stimulation could be timed to occur at different times during the step cycle (which at a walking speed of 0·5 m/s usually lasted 850 ms; see Armstrong & Drew, 1984*a*).

Stimulation was applied intermittently, a few stimulated paces alternating with similar groups of unstimulated paces. When stimulation was applied during successive paces there was no progressive increase or decrease in the responses, nor did repeated use of individual cortical electrodes lead to any response diminution indicative of cortical damage.

Data processing

E.m.g. signals were amplified and stored after amplification on FM channels of an instrumentation tape recorder (Racal Thermionic Store 7D) along with a voice log, a stimulus marker, and a time code (see Armstrong & Drew, 1984*a*). Over-all band width was 100 Hz–1·3 kHz. Four e.m.g.s were usually recorded simultaneously but in one animal the experiment was repeated so that additional muscles could be studied. On such occasions brachialis was always recorded to check for comparability between the different bouts of locomotion.

The natural locomotor bursts of e.m.g. were full-wave rectified and displayed using an ink-jet recorder (Minograf; Elema-Schonander). Activity during selected groups of paces was also digitized, rectified and averaged using a PDP11/34 computer. Usually 20 'stimulated' paces were compared with the same number of 'unstimulated' paces. In order to display best the e.m.g. changes evoked by cortical stimulation a program was available to display only that part of the averaged step cycle in which the stimulus occurred (or the corresponding time segment for 'unstimulated' paces).

The procedure is clarified by Fig. 1. Fig. 1*A* shows the time relations expected during one pace for the normal locomotor activity in the four muscles most frequently recorded. The horizontal bars indicate for each muscle the average duration of its active period at a walking speed of 0·5 m/s. Fig. 1*B* shows the usual form of the voltage envelope enclosing the rectified e.m.g. signal from each

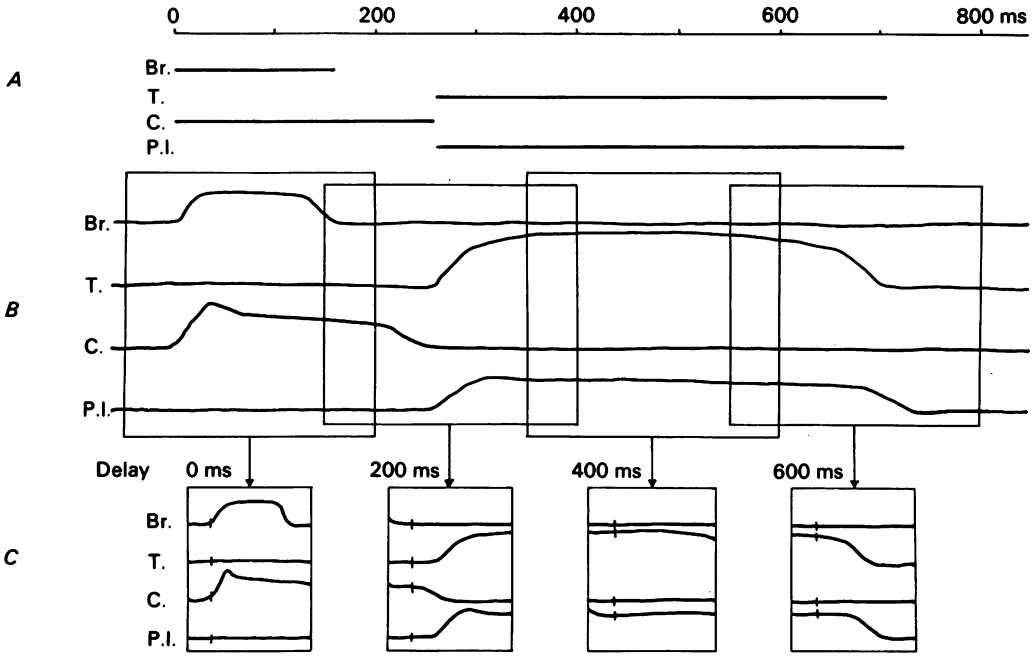

Fig. 1. Diagram illustrating the method used to display e.m.g. responses evoked by cortical stimulation applied at different times during the step cycle. *A*, horizontal bars indicate durations and relative timings for the locomotor e.m.g.s in four different muscles of the forelimb during locomotion at 0·5 m/s. Step cycle is taken as beginning at onset of locomotor e.m.g. in brachialis (Br.) muscle and lasts 850 ms. The data are the averages of measurements made for many paces in several animals. Swing begins very shortly (*ca.* 30 ms) after brachialis onset; stance begins very shortly (*ca.* 30 ms after e.m.g. onset in triceps brachii lateral head (T.); see Armstrong & Drew (1984*a*). C., cleidobrachialis; P.l., palmaris longus. *B*, schematic representation of the typical voltage envelope which encloses the (rectified) locomotor e.m.g. in each of the four muscles. The windows enclose the parts of the step displayed by the computer when stimuli are presented 0, 200, 400 and 600 ms after onset of locomotor e.m.g. in brachialis. Note each window has duration 250 ms. *C*, same four 250 ms windows as in *B*, shown without overlap. Vertical marks show times of stimulus onset; each window includes a period of 50 ms before stimulus onset. Any responses to cortical stimulation will occur superimposed on the locomotor-related e.m.g. activity shown within the windows.

muscle. On this semi-diagrammatical record are superimposed four time windows which are shown without overlap in Fig. 1*C*. These displays show the idealized form of record expected if ineffective cortical stimuli were applied at delays of 0, 200, 400 and 600 ms after the onset of locomotor activity in brachialis muscle. Note that each display covers 250 ms and includes a 50 ms pre-stimulus period. This accounts for the fact that the display for delay 0 begins before the onset of activity in brachialis and the other flexor muscle (cleidobrachialis). When effective cortical stimuli are used the e.m.g. responses will occur superimposed on a varying background level of natural locomotor activity similar to that seen in the diagrams in Fig. 1*C*. The times when stimulus onset would occur are indicated in Fig. 1*C*.

In subsequent Figures only the results for delays of 0, 200, 400, 600 and 700 ms are presented but observations were also made at delays of 100, 300 and 500 ms. Note that using real data there will be some natural fluctuation in the duration of the step cycle and the locomotor e.m.g. bursts. Although data were rejected if the variation in step duration exceeded plus or minus 10%, the variations will result, after averaging, in a more gradual rise and fall of the locomotor activity in

each muscle than was actually observed in the individual paces. Voltage calibrations were not applied to the averaged records because comparison with the amplitude of the locomotor bursts provides a more meaningful indication of response size. The locomotor bursts were usually 1–2 mV in peak amplitude.

Pyramidectomy

In three animals stimulation was carried out both before and 1 week after section of the medullary pyramid (see Armstrong & Drew (1984*c*) for operative details and histological control procedures). In one animal a sham operation, in which the pyramid was exposed but not sectioned, was carried out as a control. In this case the responses were unchanged as compared with those obtained pre-operatively.

RESULTS

General

A total of twenty-two chronically implanted micro-electrodes was used (in five cats) to deliver intracortical microstimulation to the motor cortex whilst the animals walked slowly and steadily at 0·5 m/s. Each electrode recorded single-unit action potentials or multi-unit activity and we conclude, therefore, that the electrode tips lay in the grey matter rather than the subcortical white matter (cf. Armstrong & Drew, 1984*a*, 1985).

To facilitate comparison with previous studies in which microstimulation has been employed in the pericruciate cortex of the cat (see Asanuma, 1975 for references; also Asanuma, Arnold & Zarzecki, 1976) stimuli were usually applied as brief trains of 11 pulses at 330 Hz, intensity 5–20 μA. The effects of such a train were brief and, as judged from the e.m.g. signals, were confined to the pace in which it was delivered. However, longer trains were occasionally used and these sometimes produced larger effects on the musculature, leading to resetting of the step cycle rhythm (see later).

All twenty-two electrodes were within the forelimb area of the motor cortex (i.e. in the coronal gyrus and the immediately adjoining parts of the anterior and posterior sigmoid gyri; cf. Armstrong & Drew, 1985). Each electrode had previously been shown to evoke a flick movement of the contralateral forelimb when 35 μA stimuli were delivered in the resting animal (see Armstrong & Drew, 1984*c*). As explained in the Methods, e.m.g. activity was recorded from a range of muscles in the contralateral forelimb, including muscles acting at the shoulder, elbow and wrist joints and on the digits. Effects were studied first using 20 μA stimuli, and intensities of 15, 10 and 5 μA were sometimes employed subsequently. In most cases at least one muscle had a response threshold lower than 10 μA and in some cases e.m.g. changes were still evident at currents less than 5 μA.

Range of e.m.g. responses evoked by 20 μA cortical stimulation

Fig. 2 illustrates typical e.m.g. responses evoked from one electrode which was located at the junction of the anterior sigmoid and coronal gyri. The traces in Fig. 2*A* show rectified e.m.g. signals recorded simultaneously from four muscles: lateral head of triceps brachii (T.), brachialis (Br.), palmaris longus (P.l.) and cleidobrachialis (C.). Each muscle generated one locomotor burst of e.m.g. per step cycle and the bursts in cleidobrachialis and brachialis, both of which are flexors, occur nearly synchronously. These muscles are, however, active markedly out of phase with the other two muscles, both of which function as extensors during locomotion.

At intervals during the walking, brief trains of cortical stimuli were delivered. As shown by the top trace in Fig. 2*A*, which is a stimulus marker, trains were delivered during each of the four paces shown, after which a group of 'unstimulated' paces was followed by another group of 'stimulated' paces (neither of these is shown). This alternation was continued until at least twenty 'stimulated' and twenty 'unstim-

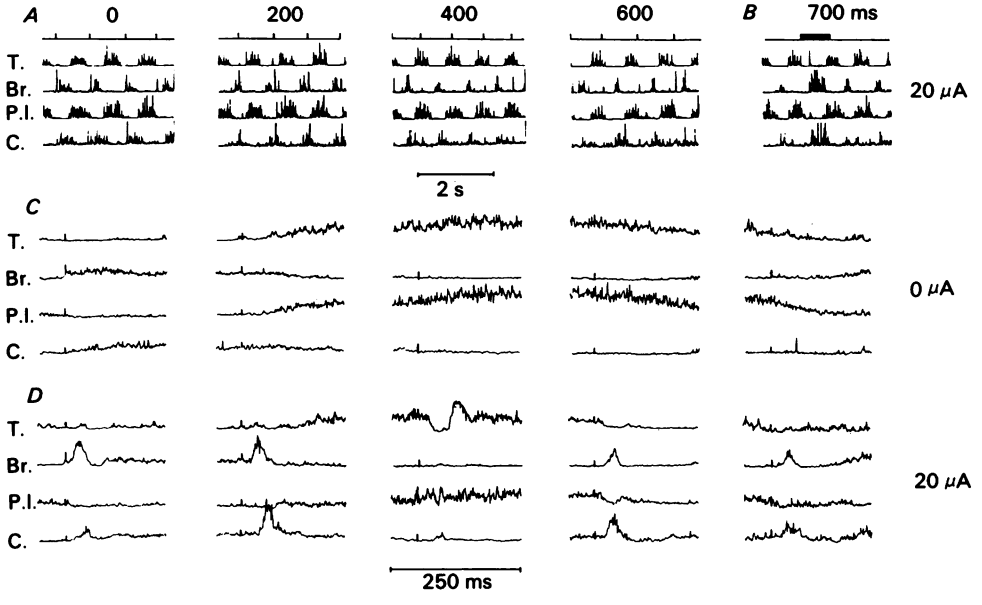

Fig. 2. E.m.g. responses evoked in four muscles by stimulus trains delivered via one cortical micro-electrode at different times in the step cycle. *A*, rectified e.m.g.s for groups of four paces during each of which the onset of stimulation at 20 μA was delayed relative to brachialis onset by the time shown (0, 200, 400, 600 ms). Top trace is a stimulus monitor. Muscle abbreviations as in Fig. 1. Time calibration applies to all four groups of traces and to *B*. *B*, responses evoked during walking by a prolonged (850 ms) stimulus train which began 700 ms after the first displayed locomotor e.m.g. in brachialis (cf. Fig. 8 and see text). *C*, displays similar to Fig. 1*C* and obtained by computer-averaging the locomotor e.m.g.s during twenty successive paces. Stimulus delays (relative to brachialis onset) are shown above. Stimulus intensity in these control traces was 0 μA. *D*, displays as in *C* but cortical stimulus intensity 20 μA. Time bar below *D* applies to all traces in *C* and *D*.

ulated' paces were available for averaging and comparison (see Methods). From the stimulus marker trace it can be seen that this sequence was repeated with the stimuli applied at different times during the step cycle. The times ranged in 100 ms steps from 0 ms (when stimulus train onset coincided with the onset of locomotor activity in brachialis muscle) up to 700 ms (not shown in Fig. 2*A*). Throughout collection of the data the average pace duration was *ca.* 850 ms as measured from the intervals between successive bursts of e.m.g. in any one muscle. Altering stimulus timing in this way allowed detection of any dependence of the responses on the phase of the step chosen for stimulus delivery (cf. Drew & Rossignol, 1984).

Fig. 2*A* shows that brief stimulation did not produce any gross change in the

locomotion since the step cycle was not reset, and there were no major changes in the phase relations between the different e.m.g.s. However, significant responses were produced in each muscle at most stimulus timings illustrated. To take only the most obvious effects, at delay 600 s brachialis was activated briefly at an inappropriate time (i.e. during the stance phase of the step when this muscle normally generates no e.m.g.) while by contrast, at delay 400 ms the natural locomotor burst in the lateral head of triceps brachii was interrupted briefly in each pace. This latter effect exemplifies that stimulation was frequently capable of eliciting inhibitory as well as excitatory responses.

The range of effects present in Fig. 2*A* is in fact better seen by comparing Fig. 2*C* and *D*, each of which shows on an expanded time scale the rectified activity in each of the four muscles during five different 250 ms time slices of the step cycle (cf. Fig. 1). In each case the e.m.g.s during twenty paces have been computer-averaged (see Methods). Fig. 2*C* shows data collected during control (i.e. 'unstimulated'; 0 μA) paces, and comparison of the successive time slices shows that the activity in each muscle waxes and wanes once per step cycle. Fig. 2*D* shows the averages for another twenty paces, during which stimuli were applied at intensity 20 μA. The vertical mark 50 ms after the beginning of each trace shows the time of onset of the stimulus train and similar marks are placed in Fig. 2*C* to facilitate comparison of the 'stimulated' and 'unstimulated' records.

Such comparison confirms for triceps brachii that at delay 400 ms (when the muscle is maximally active), stimulation produced a temporary (but complete) cessation of the locomotor e.m.g., followed by a brief increase above the normal level. The inhibition began abruptly and at quite short latency (20 ms). Inhibition of the (waning) locomotor e.m.g. is also detectable at 600 ms, but at 0 and 200 ms when the muscle is inactive a brief and just perceptible e.m.g. (i.e. an excitatory response) was evoked (again at latency 20 ms).

In the other extensor muscle (palmaris longus) stimulation was never so effective, but at 400, 600 and 700 ms there were brief reductions in the locomotor e.m.g. By contrast, the two flexor muscles show a quite different pattern of response: both show a considerable excitation at 0 and 200 ms. At 0 ms in brachialis this is followed by some reduction in the locomotor e.m.g. activity; such biphasic actions were not uncommon (cf. triceps brachii above) but attention will henceforward be confined to initial changes. At 400 ms no significant excitatory effect is evident in brachialis though a small response appears in cleidobrachialis. At 600 and 700 ms both muscles exhibit sizeable responses and it is noteworthy that at both these times the next locomotor e.m.g. has not yet begun (some locomotor e.m.g. is visible in the later part of the 700 ms trace because the trace ends 900 ms after brachialis onset and therefore includes the initial part of the locomotor burst associated with the next pace).

It is clear from Fig. 2 (see also Figs. 5 and 9) that it will be difficult to describe concisely the complex actions produced on the various muscles from the different cortical electrodes. However, a qualitative summary is given in Fig. 3. Reading across indicates the effects elicited from each electrode while reading down indicates the range of actions exerted on particular muscles from different electrodes. The muscles are grouped as flexors or extensors depending on whether they are (solely or mainly) active in association with the swing or stance phases of the step cycle respectively.

Absence of response is represented in Fig. 3 by a cross, and responses by a full circle or a semicircle. Excitations resulting from cortical stimulation are represented by open symbols, inhibitions by filled symbols. In constructing Fig. 3 the step cycle was divided into swing and stance, and a semicircle denotes that stimulation evoked a response during only one of these two phases. A lower semicircle stands for a response

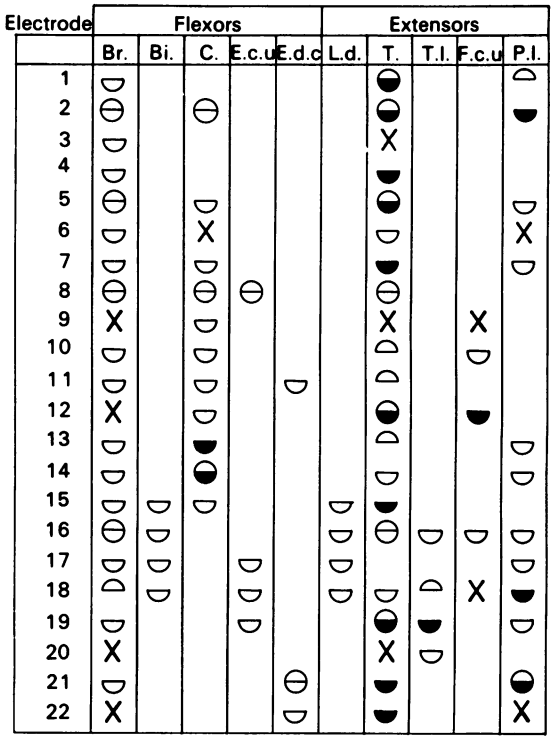

Fig. 3. The range of e.m.g. responses evoked in muscles of the contralateral forelimb by 20 μA stimulation applied via twenty-two different cortical electrodes. Electrode locations shown in Fig. 7*A*. ×, no response; ⊖ excitatory response obtained throughout the step cycle; ⊃ and ⊂ excitatory responses obtained respectively in the step phase when the muscle generates locomotor e.m.g. and in the phase when the muscle is normally inactive; ◒ reduction of the locomotor e.m.g.; ◓ excitation when the muscle is inactive plus inhibition during the locomotor e.m.g. E.c.u., extensor carpi ulnaris; E.d.c., extensor digitorum communis; L.d., latissimus dorsi; T.l., triceps brachii long head; F.c.u., flexor carpi ulnaris. Other abbreviations as in Fig. 1.

evoked during the phase when the muscle develops its locomotor e.m.g. (i.e. swing for flexors, stance for extensors); an upper semicircle denotes a response evoked during the phase when the muscle is *not* active (i.e. stance for flexors, swing for extensors). A full circle indicates a response evoked throughout the step cycle. Full circles in which the upper half is open and the lower half filled represent cases in which excitation occurred during one phase and inhibition during the other.

Fig. 3 ignores any differences in response amplitudes and also involves some simplification of the response patterns because some responses, whether excitatory

or inhibitory, were present during only part of one of the two phases. Moreover, for some phase-dependent excitations the period when a response could be evoked did not coincide precisely with either phase but embraced part of both. In such cases the symbol in Fig. 3 is chosen to represent the phase in which a response was most evident. Note that stance and swing are not equal in duration: stance occupies approximately 67 % of the step during walking at 0·5 m/s (see Armstrong & Drew, 1984*b*).

Some features of Fig. 3 require comment. First, the flexor and extensor groups of muscles differed markedly in that inhibitory actions were much commoner in extensors: with the exception of latissimus dorsi each of the five extensors was inhibited at least once. Taking into account the numbers of cortical electrodes and muscles studied there were forty-seven opportunities to observe an inhibitory effect on an extensor muscle and sixteen such effects were observed (34 % incidence); for the flexors there were forty-five opportunities but only two inhibitory effects (4·4 % incidence), both in cleidobrachialis.

For excitatory effects the situation was different: during stance excitation was detected in a flexor muscle on ten out of a possible forty-five occasions (22 %), whilst the corresponding values for extensors were twenty out of forty-seven (43 %). During swing the relative incidence was reversed because there were thirty-seven excitatory actions on flexors (82 %) but only thirteen actions on extensors (28 %).

Considering individual flexors and extensors, it is difficult to make useful comparisons because different combinations of muscles were studied in relation to the different cortical electrodes and some muscles were studied on few occasions. However, it is noticeable that individual electrodes usually exerted a similar influence over different flexor muscles, though this was not invariably the case (see especially electrodes 13 and 14). For extensor muscles few comparisons are possible but the two most often studied (lateral head of triceps and palmaris longus) tended to respond differently, suggesting a less uniform pattern of influence.

Considering the different electrodes, it is strikingly evident from Fig. 3 that at this stimulus strength (20 μA) the effect of any one electrode was hardly ever confined to a single muscle. There were fourteen electrodes for which recordings were made from four muscles, and in no fewer than nine of these there were responses evoked in all four muscles; in another case three muscles were influenced, in two cases there were responses in two muscles, and only one electrode produced changes confined to a single muscle. There were five electrodes for which more than four muscles were studied: three of these influenced five out of five muscles, another influenced all of seven muscles and the fifth influenced seven out of eight muscles. Because the number of muscles studied was rather limited it is of course possible that there were additional influences on muscles from which e.m.g. recordings were not made.

All twenty-two electrodes were also used to study the (excitatory) e.m.g. responses evoked by stimulation at 35 μA in the resting animal (see Armstrong & Drew, 1985). In some cases the combination of muscles recorded from was not the same as during locomotion but there were nevertheless eighty-nine instances when the responsiveness of a particular muscle to stimulation via a particular electrode was studied under both sets of conditions. During rest, responses were observed in fifty-nine of these instances so that on average 2·3 muscles were excited per electrode. During locomotion

excitatory responses were observed in sixty-seven of the instances so that the average number of muscles excited per electrode rose to 3·0 (despite the use of weaker stimuli). Four electrodes excited the same number of muscles during rest and locomotion while thirteen excited more muscles during locomotion and five excited fewer.

Phase dependence of the responses

Attention has already been drawn to the fact that many responses were phase-dependent (i.e. dependent on the timing of the cortical stimulation relative to the time course of the step cycle) and some information regarding this phenomenon is available from Fig. 3. However, more detailed information for some muscles is summarized in Fig. 4 in which the step is subdivided into eight portions (corresponding to the use of stimulus delays ranging from 0 to 700 ms), and the number of cortical electrodes effective during each of these is plotted in histogram form.

Fig. 4*A* presents the findings for brachialis, the flexor muscle most thoroughly studied. Inspection of Fig. 4*A* shows that throughout the swing phase (delays 0, 100 and 200 ms) most of the twenty-two electrodes were capable of eliciting an (excitatory) response. By contrast, at delays of 500 and 600 ms (i.e. in mid-stance) only a few electrodes evoked a response (which was usually small). Note, however, that at a delay of 700 ms the number of effective electrodes rose again. At this time locomotor activity had not yet begun again in the muscle so that its 'accessibility' to cortical influence was increasing before the onset of the next locomotor burst.

The two other elbow flexors, biceps brachii and cleidobrachialis were studied less often but, as Fig. 4*C* shows, there were enough observations on cleidobrachialis to demonstrate that it closely resembled brachialis in the pattern of its phase dependence for excitatory effects (as also did biceps). In cleidobrachialis there were two inhibitory responses (cf. Fig. 3) and these occurred at delays of 100 and 200 ms (i.e. during swing). Phase dependence for excitatory responses in the wrist and digit flexors (taken together) also followed precisely the same pattern as for brachialis (see Fig. 4*B*).

Turning to the extensors, it is necessary to consider separately the excitatory and the inhibitory effects, and for lateral head of triceps these are plotted respectively above and below the horizontal axis in Fig. 4*D*. Here, the number of electrodes producing excitation is seen to peak at a delay of 200 ms (just before onset of the normal locomotor burst of e.m.g.). However, the Figure also shows that excitation was more often produced at delays of 0 and 100 ms (when the muscle is inactive) than at any time during stance. Inhibitory effects were necessarily detectable only at delays between 200 and 600 ms but Fig. 4*D* shows that between these times the number of effective electrodes rose to a peak at 400 ms (when the locomotor e.m.g. was largest) and then declined.

Other extensors were studied less often but the ventroflexors of the wrist and digits behaved similarly, and data relating to these muscles (flexor carpi ulnaris and palmaris longus) are therefore pooled in Fig. 4*E*. Unlike the case for lateral head of triceps, excitatory responses were not often evoked when the muscles were inactive but were commonest at delays of 300 and 400 ms when the muscles were reaching the peak of their locomotor activity. Inhibitory effects were observed throughout the locomotor e.m.g.

Long head of triceps was studied in relation to only four electrodes, one of which

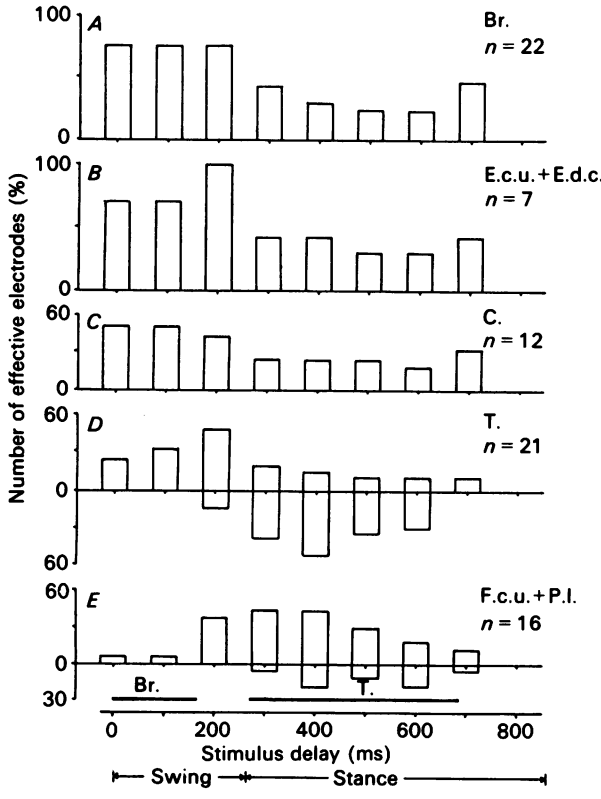

Fig. 4. Effect of stimulus timing during the step on the number of cortical electrodes producing responses in particular muscles. Each column shows the number of electrodes evoking a response, expressed as a percentage of the total number tested. *A*, excitatory responses in brachialis; twenty-two electrodes tested. *B*, excitatory responses in extensor carpi ulnaris or extensor digitorum communis; seven electrodes. *C*, excitatory responses in cleidobrachialis; twelve electrodes. *D*, responses in lateral head of triceps; twenty-one electrodes. Excitatory effects plotted above the base line and inhibitory effects below. *E*, as *D* but for flexor carpi ulnaris and palmaris longus; twelve electrodes. Horizontal bars below *E* indicate the average duration of locomotor e.m.g. in brachialis (Br.) and triceps brachii lateral head (T.).

produced a phase-dependent inhibition largest at a delay of 400 ms while the remainder gave phase-dependent excitations, one during swing and the others during stance. The remaining extensor, latissimus dorsi, was also studied four times only and the findings were somewhat surprising. In one case excitation occurred throughout the step cycle and in the others there were phase-dependent excitations during swing. This muscle therefore appeared to respond like the flexors even though its locomotor activity occurs during stance.

By expressing for all electrodes the total number of stimulus delays at which responses were observed as a percentage of the over-all number tested it was possible to obtain a numerical index of 'accessibility' to cortical influences for each muscle studied. The results are given in Table 1 where excitatory and inhibitory responses

TABLE 1. 'Accessibility' of different muscles to cortical influences

Muscle	Excitation (%)	Inhibition (%)
L.d.	50	0
E.c.u. + E.d.c.	50	0
Br.	47	0
Bi.	36	3
C.	33	4
F.c.u. + P.l.	27	8
T.l.	22	6
T.	21	20

Muscle abbreviations as in Figs. 1 and 3.

are tabulated separately; the muscles are rank-ordered in descending order of susceptibility to excitatory influence and, not surprisingly (in view of the data in Fig. 3), the flexors and latissimus dorsi were more 'accessible' than the extensors. For inhibitory responses the rank-ordering was almost exactly opposite to that for excitations. Inhibitory influences were also over-all less frequent and to an extent which cannot be wholly accounted for on the basis that they were potentially detectable only when the muscles were active. One limitation of Table 1 is that different muscles were studied in relation to different numbers of cortical electrodes and there was often incomplete overlap between the electrode populations (see Fig. 3). Because the electrodes were scattered throughout the forelimb motor cortex (see Fig. 7) some influence of cortical somatotopy on the rank-orderings cannot be excluded.

Effect of stimulus intensity

For each cortical electrode the actions were examined at two or three intensities below 20 μA. For six of the twenty-two electrodes (27 %) the threshold for producing a detectable effect on at least one muscle was less than 5 μA and for a further five electrodes it was less than 10 μA. In the other cases the lowest threshold lay between 10 and 20 μA.

The effect of reducing stimulus intensity is illustrated for one electrode in Fig. 5 using the same form of presentation as in Fig. 2. All the effects visible at 20 μA are still present at 10 μA. However, at 5 μA there is no excitatory effect on triceps at 0 ms delay and responses are barely detectable in palmaris longus. In both flexor muscles (cleidobrachialis and brachialis) 5 μA stimuli elicit a response only when stimulation coincides with the onset of the step cycle (0 ms) or just precedes the next step (700 ms).

In general the effects of reducing stimulus strength were to reduce the amplitude of the responses, to reduce the number of muscles influenced, to increase phase dependence and sometimes to increase the latency of the responses. It is of particular interest that even the weakest stimuli (5 μA) occasionally produced a transient but complete interruption of the locomotor e.m.g. in lateral head of triceps (cf. Fig. 4, 400 ms delay).

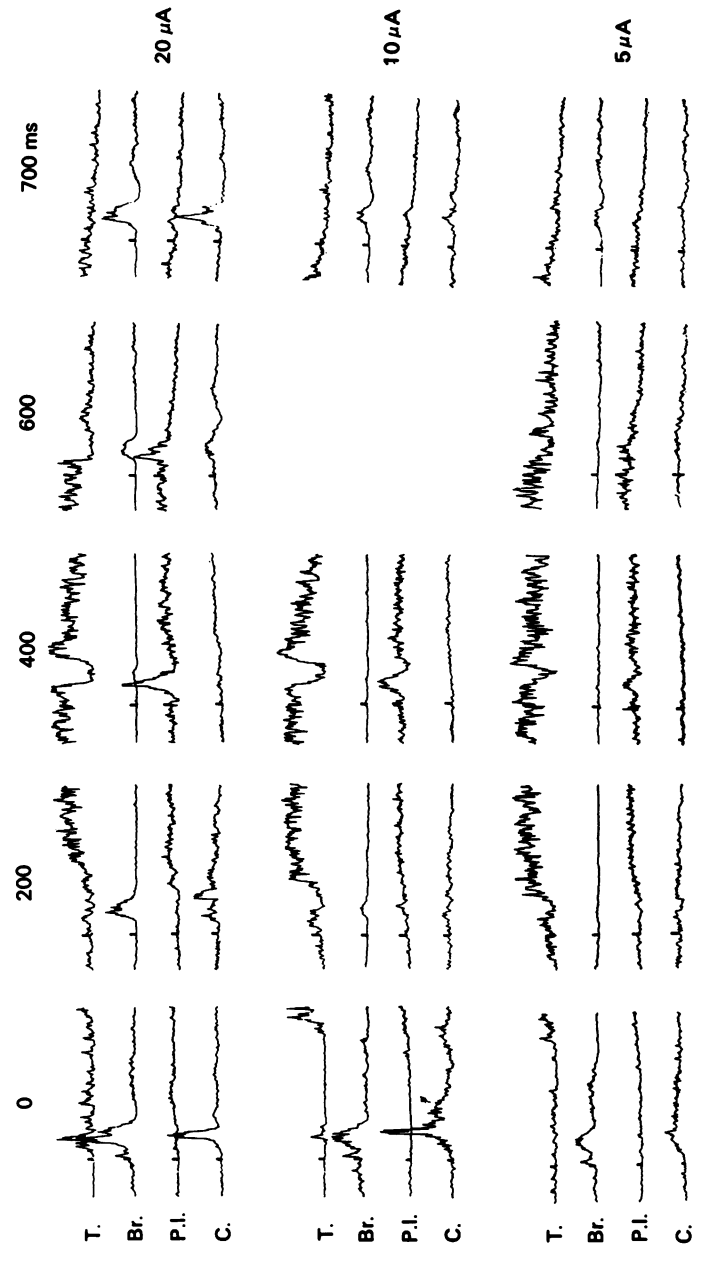

Fig. 5. Effect of stimulus intensity on e.m.g. responses. Form of display similar to Fig. 2 but with the control (0 μA) traces omitted. Muscle abbreviations as in previous Figures.

Response latencies

The latencies of the responses to cortical stimulation (at intensity 20 μA) varied quite widely from a minimum of 6 ms (measured from the first stimulus in the train) up to values occasionally in excess of 40 ms. Large latency differences were often evident both for responses evoked in different muscles from a single electrode and for responses evoked in any one muscle from different electrodes. However, for excitatory responses the *shortest* latencies encountered were not grossly different between muscles. They were 6 ms for each locomotor flexor (brachialis, cleidobrachialis, biceps brachii, extensor carpi ulnaris and extensor digitorum communis) and for lateral head of triceps and palmaris longus, 10 ms for latissimus dorsi and 11 ms for long head of triceps and flexor carpi ulnaris. A value of 6 ms is short enough (see Discussion) to indicate that a single stimulus was sufficient to initiate the response and this was occasionally confirmed directly, most often for brachialis.

For inhibitory responses the minimum latencies were also short. For both muscles in which e.m.g. reductions were most frequent (lateral head of triceps and palmaris longus) the shortest latency was 6 ms, i.e. identical with the minimum excitatory latencies for these muscles.

Such brief latencies were infrequent. When the shortest values found in individual muscles from each effective electrode were averaged, the mean values for excitatory responses were: brachialis 8·8 ms, cleidobrachialis 16·5 ms, extensor carpi ulnaris 11·5 ms, lateral head of triceps 12·3 ms and palmaris longus 13·1 ms. In the other muscles there were too few observations to provide useful means.

In obtaining the above values those few latencies which exceeded 40 ms have been excluded. In addition there were a few responses for which the latency could not be estimated accurately either because response onset was very gradual or because the averaged traces for the control and the stimulated groups of paces were too noisy.

For inhibitory responses in lateral head of triceps and palmaris longus the mean latencies were 18·0 and 10·3 ms respectively.

Latency frequently fluctuated slightly from step to step and in addition some muscles showed systematic latency fluctuations during the course of the step cycle. This dependence of latency on stimulus timing was investigated and the results for brachialis and lateral head of triceps are shown in Fig. 6, in which the mean latency of the responses evoked from the different electrodes is shown for each of the eight different stimulus timings. In brachialis (Fig. 6*A*) it is clear that the latency of the (excitatory) responses was shortest at a stimulus delay of 0 ms. Thereafter latency increased to a maximum at the middle of stance and subsequently shortened again. Because many of the responses were phase-dependent the number of responses (and therefore the number of cortical electrodes: cf. Figs. 3 and 4) differs between histogram columns. However, for each of the four individual electrodes which evoked responses at all eight delays, there were latency variations which paralleled precisely these in Fig. 6*A*.

In cleidobrachialis also, mean latency was shortest (12·8 ms; $\pm$5·4 ms, S.D.) at 0 ms delay though maximum latency (29·8 ms; $\pm$4·8 ms) was reached earlier (at 200 ms delay). Again this pattern was mirrored by the two electrodes which evoked excitatory responses throughout the step cycle. There were too few responses in other

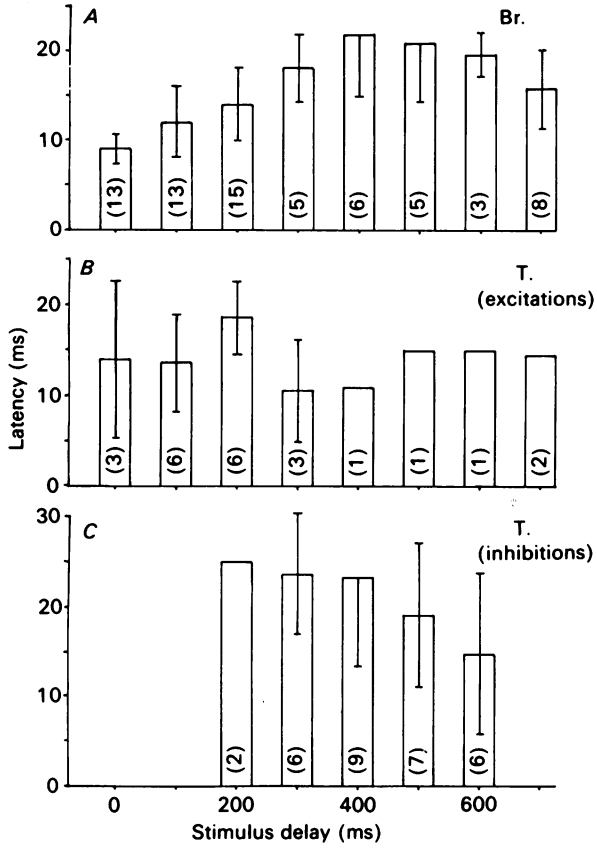

Fig. 6. Histograms showing the dependence of response latencies on stimulus timing relative to the step cycle. Column heights indicate mean latency for the responses evoked from those cortical electrodes able to evoke a response at each stimulus delay relative to brachialis onset. Number of electrodes involved at each delay is shown in parentheses. Bars indicate S.D. about mean. *A*, excitatory responses in brachialis. *B* and *C*, respectively excitatory and inhibitory responses in lateral head of triceps brachii.

flexors to give worthwhile means but for the individual electrodes latencies were always least when stimulation was delivered during the locomotor e.m.g.

For lateral head of triceps the latency data for excitatory responses are presented in Fig. 6*B*. Unfortunately, at delays of 400, 500 and 600 ms latency measurements were available in respect of one electrode only, but at other delays latency did not vary systematically, and for the one electrode for which latencies could be measured at all eight delays there was no systematic change in latency during the step cycle. A similar lack of dependence of latency on stimulus timing was evident for the responses evoked from other individual electrodes and was also found for the excitatory responses evoked in the digit extensor (palmaris longus).

The results for inhibitory responses in lateral head of triceps are given in Fig. 6*C*; latency became progressively shorter as the stimulus was presented successively later during the locomotor e.m.g.

Cortical topography

Eleven micro-electrodes were inserted into the coronal gyrus, two into the lateral part of the posterior sigmoid gyrus and nine into the anterior sigmoid gyrus. In each experiment their entry points into the cortex were charted on a photograph of the brain surface and subsequently transferred to a standard scale diagram of the pericruciate area (cf. Armstrong & Drew, 1984, 1985).

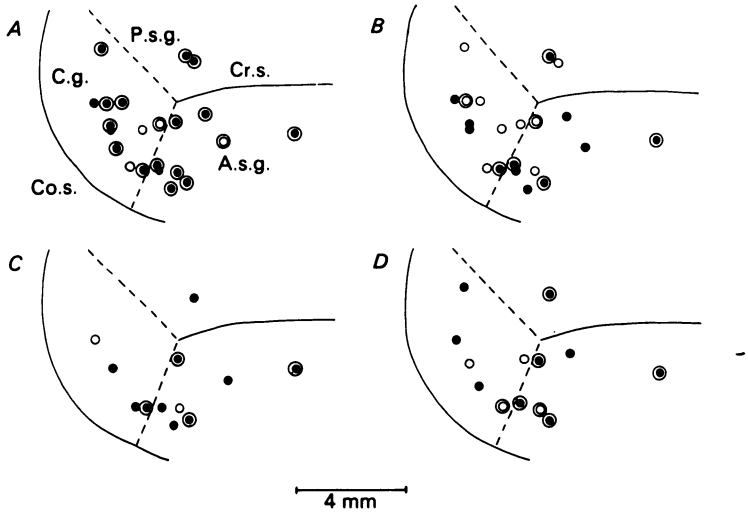

Fig. 7. Scale diagrams of the surface of the right pericruciate cortex to show distribution of micro-electrodes evoking responses in different muscles. ●, electrodes which evoked excitatory responses during locomotion; ○, electrodes evoking no response during locomotion (or purely inhibitory responses); encircled points, electrodes which evoked excitatory responses when used to deliver 35 μA stimuli in the resting animal. *A*, *B*, *C* and *D* are for brachialis, lateral head of triceps cleidobrachialis and palmaris longus respectively. Cr.s., cruciate sulcus; Co.s., coronal sulcus; P.s.g., posterior sigmoid gyrus; A.s.g., anterior sigmoid gyrus; C.g., coronal gyrus.

All twenty-two electrodes were tested against brachialis muscle (see Fig. 3) and their positions are therefore all given by Fig. 7*A* which shows those electrodes which did (●) and did not (○) evoke excitatory responses in brachialis when 20 μA stimuli were applied during locomotion (for further explanation of the symbols see below). Most electrodes did evoke responses (cf. Fig. 3) so that, as regards cortical topography, Fig. 7*A* demonstrates only that responses could be evoked from loci scattered rather widely across the forelimb motor cortex.

Similar maps for lateral head of triceps, cleidobrachialis and palmaris longus are given in Fig. 7*B*, *C* and *D* respectively (for the other muscles too few electrodes were tested to provide useful maps). Because most electrodes evoked responses in several muscles it is not surprising that Fig. 7 yields no evidence that different muscles were 'represented' in different parts of the motor cortex.

Some additional information can, however, be derived from Fig. 7. All the micro-electrodes were also used to deliver stimulation at intensity 35 μA in the resting

animal, and in Fig. 7 the encircled symbols represent electrodes which evoked excitatory responses during rest. For brachialis (Fig. 7*A*), which was readily excited during rest, there were only three electrodes which produced responses during locomotion but not during rest (encircled filled symbols) and there were also three which produced responses during rest but not during locomotion (encircled open symbols). For each of the other three muscles, however, the electrodes from which excitation was evoked only during locomotion made up a substantial proportion of the total and there were fewer electrodes which evoked responses only during rest. These muscles were, therefore, 'accessible' from more cortical loci during locomotion than rest.

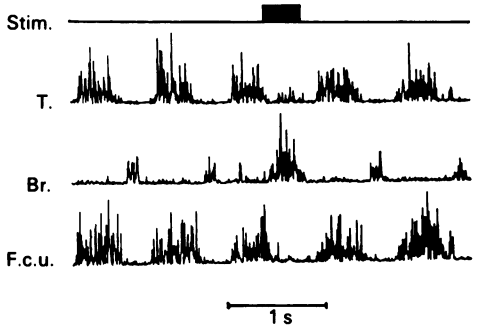

Fig. 8. Resetting of step cycle in contralateral forelimb by long-train cortical stimulation. Rectified e.m.g.s displayed (not averaged) by the computer. Train onset occurred 700 ms after brachialis onset and train duration was 385 ms. Stimulus intensity 20 μA. Muscle abbreviations as in previous Figures. Stim., indicates stimulus marker trace.

Responses to longer stimulus trains

Stimulus trains normally lasted 33 ms (11 pulses; 330 Hz) but much longer trains were occasionally given and found to produce more substantial e.m.g. changes. An example is given in Fig. 8 in which a micro-electrode in the lateral part of the posterior sigmoid gyrus was used to apply a 20 μA train lasting 385 ms during one of the five paces. Stimulus onset occurred near the end of the locomotor bursts in lateral head of triceps and flexor carpi ulnaris (i.e. late in stance). The extensor bursts were slightly curtailed but the largest effect was on brachialis: its locomotor burst began earlier and was greatly increased both in amplitude and in duration. At the same time the duration of the inactive phase in the extensors was prolonged (though note that some e.m.g. was evoked during this phase in triceps). The stimulation therefore led to a resetting of the step cycle rhythm. Translated into terms of limb trajectory, stance was shortened and swing began early; the elbow was hyperflexed so that swing was prolonged and the next footfall was delayed. After the resetting a normal rhythm was resumed.

Such effects were not studied systematically but another similar example is shown in Fig. 2*B*: at stimulus delay 700 ms a train lasting 850 ms was delivered during one pace and the step cycle was reset.

Effects of pyramidectomy

In three animals the responses were studied both before and 1 week after transection of the medullary pyramid ipsilateral to the cortical electrodes.

Typical findings are illustrated in Fig. 9. Stimulation at intensity 20 μA before pyramidectomy (Fig. 9*A*) evoked clear-cut excitatory responses in all three muscles shown, but after operation higher intensity (35 μA) stimulation (Fig. 9*B*) evoked no

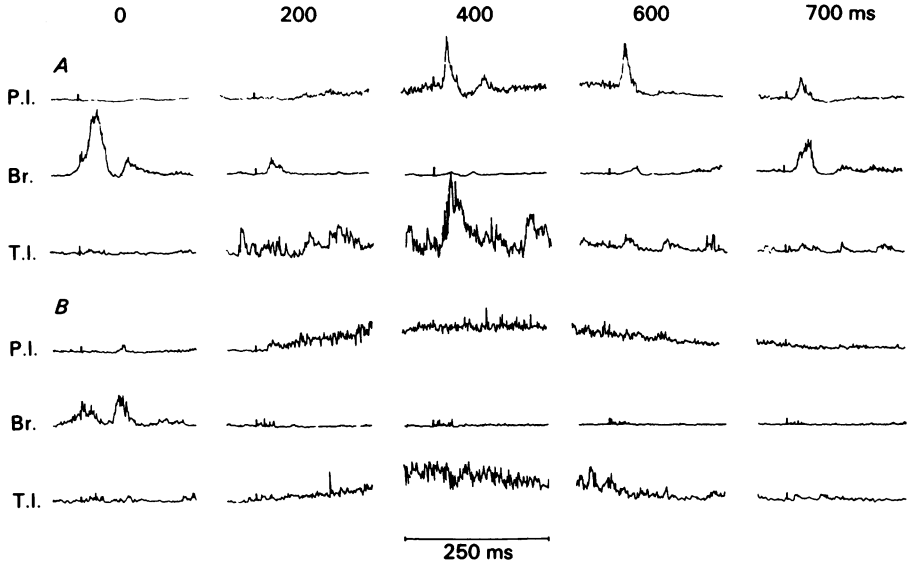

Fig. 9. Effect of pyramidectomy on the e.m.g. responses to cortical stimulation during locomotion. Display format as in Fig. 2. *A* and *B* are both averages of twenty successive paces. *A*, 20 μA stimulation before pyramidectomy. *B*, 35 μA stimulation 7 days after pyramidectomy.

response in palmaris longus or long head of triceps and the response in brachialis was confined to a much reduced excitation which appeared only when the stimulus occurred at the onset of the locomotor e.m.g. Stimulation at 20 μA evoked no response.

In general, few responses were obtainable from any electrode after pyramidectomy and for those which could be obtained both threshold and latency were always markedly increased. It seems unlikely that the losses are attributable to any generalized depression of the spinal cord because the locomotor e.m.g.s were similar in amplitude and timing to those in normal animals.

DISCUSSION

Range of e.m.g. responses to cortical stimulation

Cortical efferent activity artificially evoked by intracortical microstimulation can produce a variety of changes in the patterns of contraction which normally occur in muscles of the cat forelimb during locomotion. Elbow muscles were studied most often but effects were also observed on muscles acting at the shoulder, the wrist and on

the digits: probably, therefore, all of the forelimb musculature is accessible to cortical influence.

Brief trains of stimuli evoked e.m.g. changes which were brief but quite often complex, in the sense that initial increases in e.m.g. were sometimes followed by decreases or vice versa. However, attention has been focused almost entirely on the earliest changes in order to reduce interpretative complications. It is possible that initial effects might lead secondarily to further changes because of volitional compensations the animal might make or because of automatic compensations. The latter might include reflex responses resulting from changes in the pattern of peripheral input from the moving limb, or responses produced by changed activity in internal feed-back pathways monitoring the excitability of motor mechanisms at the spinal or at higher levels. Because most of the effects described had latencies less than 30 ms it seems unlikely that any significant proportion of them was initiated via such indirect routes.

The e.m.g. changes included marked augmentations of ongoing locomotor e.m.g.s and these were much the commonest responses observed among those muscles which contract in relation to the swing phase of the step cycle (locomotor flexors). This fits well with previous reports that hypoflexion of the contralateral limbs is a prominent locomotor deficit seen immediately after motor cortex lesions (e.g. Adkins *et al.* 1971) or section of the medullary pyramid (Liddell & Phillips, 1944).

Stimulation was also capable of augmenting activity among muscles active in relation to stance (locomotor extensors) and indeed this was the commonest effect in palmaris longus and the only effect in latissimus dorsi (from four electrodes). However, among the extensors, especially lateral head of triceps, reductions (or abolitions) of ongoing locomotor e.m.g. were often produced. Such inhibitory effects were rarely observed in flexors (twice; in cleidobrachialis only).

In addition to these effects on the locomotor bursts of e.m.g., cortical stimulation was also often capable, in both flexors and extensors, of evoking e.m.g. at those times in the step cycle when the muscles are normally inactive. The two muscles most thoroughly studied were brachialis and lateral head of triceps which respectively flex and extend the elbow joint. Because some cortical electrodes evoked out-of-phase contraction of one of these muscles together with in-phase contraction of the other the two antagonists were not infrequently co-contracted. Such co-contraction of antagonists can probably occur at other joints, although it was in fact observed only once (for extensor digitorum communis and palmaris longus; Fig. 3; electrode 21) because few suitable recordings were made.

Comparison with previous intracortical microstimulation studies

Effects of intracortical microstimulation on the motor apparatus of the cat forelimb have previously been investigated quite intensively in the resting or the anaesthetized animal. Evoked movements and/or e.m.g. responses were studied by, among others, Sakata & Miyamoto (1968), Asanuma, Stoney & Abzug (1968), Nieoullon & Rispal-Padel (1976), Pappas & Strick (1981) and Armstrong & Drew (1984*c*, 1985) and excitability changes in motoneurone pools were measured with monosynaptic reflex testing by Agnew, Preston & Whitlock (1963), Preston, Shende & Uemura (1967) and Asanuma & Sakata (1967).

In some of these studies (e.g. Asanuma *et al.* 1968) response thresholds could be

lowered by passively manipulating the limbs (which presumably generates inputs to the spinal cord from cutaneous and deep mechanoreceptors) and e.m.g. thresholds have also been reported as being posture-dependent (Armstrong & Drew, 1985). In the present study, the thresholds for excitatory e.m.g. responses were definitely lower than in the resting animal. Individual electrodes quite often evoked in particular muscles responses at 20 μA during locomotion but not at 35 μA during rest. Although there were other electrodes which behaved oppositely they were fewer (see Fig. 7*B*, *C* and *D*) except for brachialis muscle (see Fig. 7*A*).

One indication of the extent to which thresholds were lowered is given by the finding that when the responses evoked by 35 μA stimuli in the resting animal were compared (for the same electrode–muscle combinations) with those evoked during locomotion, the average number of muscles excited was 2·3 per electrode during rest but 3·0 during locomotion. This increase occurred in spite of the lower stimulus intensity used during locomotion. Another indication is provided by the fact that whereas excitation of brachialis could be evoked (at 35 μA) from forty-one out of sixty-two electrodes (66 %) during rest (see Armstrong & Drew, 1985) the proportion (for 20 μA) was increased during locomotion to eighteen out of twenty-two (82 %). For lateral head of triceps brachii, the proportion was increased more markedly, from eighteen out of sixty-two (29 %) to twelve out of twenty-one (57 %).

In the resting animal, locomotor flexors were more 'accessible' to cortical stimulation than extensors (Armstrong & Drew, 1985). It is interesting that, despite the changes in threshold wrought by the presence of locomotor activity, this differential persisted (compare Table 1 with Fig. 3*A* and *B* of Armstrong & Drew, 1985). Only latissimus dorsi altered substantially, from being the least 'accessible' muscle to being equal first with the locomotor flexors of the wrist and digits. It should be remembered, however, that during locomotion this muscle was studied in relation to only four electrodes.

It is possible that thresholds were lower during locomotion because the motor cortex became more excitable. Such a mechanism is, however, unlikely to provide the sole (or even a major) explanation. Natural impulse activity in motor cortical neurones is greatest in mid-to-late stance (Armstrong & Drew, 1984*b*) and pyramidal tract neurones recorded via micro-electrodes which evoke elbow flexions during rest are, in particular, much more active in late stance than during swing. It might therefore be expected that their responsiveness to microstimulation would then be greatest. However, in the present experiments excitatory effects on flexors were produced from many more cortical electrodes during swing than during stance. Flexor responses also displayed shorter latencies and larger amplitudes during swing than stance. The possibility must of course be considered that the natural discharges of the cortical neurones rendered them more refractory to stimulation during mid-to-late stance but it seems unlikely that such an occlusive effect was important because at this time inhibitory effects were most readily produced in extensors. We conclude that the increased accessibility of forelimb muscles during locomotion was due mainly to an increased responsiveness of spinal cord circuits to descending volleys. A similar conclusion has been reached in a recent study of the effects of microstimulation of the medullary reticular formation during locomotion (Drew & Rossignol, 1984).

The inhibitory effects observed during locomotion were not unexpected because

previous studies with monosynaptic reflex testing (e.g. Agnew *et al.* 1963; Preston *et al.* 1967; Asanuma & Sakata, 1967) have revealed that the first effect of pyramidal volleys on extensor motoneurone pools is frequently to reduce their excitability. Our finding that inhibitory effects were almost confined to extensor muscles is in good agreement with these studies and with other evidence (e.g. Lundberg & Voorhoeve, 1962) that pyramidal volleys generally affect extensor and flexor motoneurones reciprocally, the former being inhibited and the latter facilitated.

Pyramidectomy

One week after unilateral pyramidectomy the excitatory and inhibitory responses to 20 μA stimulation were virtually abolished while locomotor e.m.g.s were not noticeably changed. This suggests strongly, though it does not prove, that the responses were mediated largely via the corticospinal tract. Some responses could still be evoked if stimulus intensity was increased but they were much smaller and showed increased latency. This parallels the results of Lewis & Brindley (1965) who showed in the monkey that movements were still evokable by motor cortex stimulation after pyramidectomy though thresholds were much increased and the movements much weaker.

Response latencies

For all but three of the muscles (and these were studied infrequently), the shortest latencies for excitatory responses were 6 ms. Such a value is sufficiently short that only the first stimulus in the train can have generated the earliest part of the response. Moreover, when allowance is made for corticospinal conduction time, for conduction time in the α-motoneurone axons and for a neuromuscular delay, no more than 2 ms remains for events within the cervical cord. It is known that the shortest pathway from the corticospinal axon terminals to the α-motoneurones always includes at least one spinal interneurone (Asanuma, Stoney & Thompson, 1971; Illert, Lundberg & Tanaka, 1977; Illert, Lundberg, Padel & Tanaka, 1978) and it seems probable that the earliest responses were initiated via this disynaptic pathway.

The earliest responses in the resting animal had longer latencies (see Armstrong & Drew, 1985), the difference ranging in most muscles from 5 to 8 ms. This difference reflects the fact that in the absence of ongoing movement three descending volleys were needed to produce sufficient temporal summation in the pathway to discharge the spinal interneurones and subsequently the motoneurones (Armstrong & Drew, 1985; cf. Illert *et al.* 1976). Locomotor activity presumably increases the excitability of the interneurones enough to remove this requirement for temporal summation. If it is assumed that weaker microstimulation excites fewer cortical efferent neurones then the fact that thresholds as well as latencies are reduced presumably implies that less spatial summation is also required during locomotion.

Phase dependence of responses

Some electrodes excited individual flexor muscles throughout the step cycle but most flexor excitations were phase-dependent. As a result the number of electrodes exciting flexors was greatest during swing (see Fig. 4). Response latency was least at this time (see Fig. 6) and amplitude was also greatest. The 'accessibility' of flexor

motoneurone pools therefore varied approximately in parallel with the stepping-related changes in the excitability of these pools. In consequence it cannot be decided whether the spinal interneurones mediating the responses also show any step-related fluctuation in excitability (but see below).

For excitations in extensors the findings were less straightforward. For the extensors of the wrist and digits, as for flexors, the number of effective cortical electrodes was greatest when the muscles were active (i.e. during stance) but for lateral head of triceps it was greatest during swing (see Fig. 6*B*), when the motoneurones are not firing. This implies that the spinal interneurones mediating excitation to triceps must be more excitable during swing than stance and they cannot therefore be identical with those which excite the wrists and digit extensors.

One puzzling finding was that (based on a limited number of observations) the excitatory latencies in extensors did not appear to vary systematically during the step cycle. This difference from the flexors cannot be explained but it does perhaps suggest that the lengthening of flexor latencies during stance does not necessarily arise simply because the motoneurones are then less excitable. The rather direct path to the flexor motoneurones which is open during swing may fail to transmit during stance. If this were the case then the interneurones concerned could not also function as a link within the path by which excitatory responses are mediated during stance to the wrists and digit extensors; they could, however, be involved in producing phase-dependent excitation of lateral head of triceps.

Inhibitory effects in extensors were detectable only during the locomotor e.m.g. so there is no way of knowing whether the relevant spinal mechanisms were operative throughout the step cycle. However, the number of electrodes acting on lateral head of triceps was greatest in mid-stance and latency became progressively shorter during stance.

Cortical topography

In the anaesthetized or the resting animal e.m.g. responses are most readily evoked from two areas within the motor cortex, one in the most lateral part of the anterior sigmoid gyrus and the other in the middle of the coronal gyrus (Pappas & Strick, 1981; Armstrong & Drew, 1985). Most of the present micro-electrodes were in these areas. However, excitatory responses were sometimes evoked (at 20 μA or less) from electrodes elsewhere, including two electrodes in the lateral part of the posterior sigmoid gyrus and one rather medial on the anterior sigmoid gyrus. It is likely therefore that during locomotion responses can be evoked from a fairly wide area. However, the dual representation of excitatory efferent function evident during rest may not be completely obscured because for brachialis three of the five electrodes which gave no response at 20 μA were in the cortex which lies between the two low threshold areas (see Fig. 7*A*; cf. Fig. 5 of Armstrong & Drew, 1985). Similarly, for lateral head of triceps (Fig. 7*B*) and palmaris longus (Fig. 7*D*) there were electrodes in this area and they failed to evoke excitatory responses. Inhibitory responses were produced often only in lateral head of triceps and the electrodes concerned were intermingled apparently randomly with those evoking excitatory responses.

When a stimulus intensity of 5 μA was used the number of muscles responding per

electrode was reduced. However, responses were sometimes still present in several muscles and these did not necessarily act about the same joint. In view of current uncertainties regarding the mechanisms by which intacortical microstimulation acts on the motor cortex the volume of cortex influenced by such stimuli cannot be defined precisely (see Asanuma, 1975 and Phillips & Porter, 1977 for discussions). However, such findings do suggest that rather complex motor outputs can be evoked from what are probably quite small portions of the motor cortex.

Functional implications for the neural control of locomotion

During steady walking over a flat surface neurones in the cat motor cortex, including many pyramidal tract neurones, discharge rhythmic bursts of impulses time-locked to the step cycle in the limbs (Armstrong & Drew, 1984*a*). The utility of these discharges as control signals for locomotor movement is, however, open to debate, particularly in view of the transient nature of the deficits produced in this kind of locomotion by lesions of the pyramid or the motor cortex (Liddell & Phillips, 1944: Adkins *et al.* 1971). Nevertheless, the demonstration that electrically evoked activity can powerfully influence the limb muscle e.m.g.s, must suggest that natural discharges into the pyramidal tract are likely to contribute actively to locomotor control.

Armstrong & Drew (1984*a*) reported that when the speed of locomotion was increased (from 0·37 to 1·43 m/s) a small proportion (14 %) of cortical neurones showed a progressive change (usually an increase) in peak and mean discharge rate but most cells showed no such change. In addition, there were no substantial changes in firing as between walking on the flat and up to 10° incline. Because both changes in the locomotion involve considerable increases in limb muscle e.m.g.s, these largely negative findings were taken to suggest that the discharges were probably concerned mainly with regulating aspects of locomotion other than the force levels developed by the muscles.

However, microstimulation can increase substantially the amplitude of the locomotor e.m.g.s in the limb flexors and can also augment or (more often) reduce those in limb extensors. This suggests that natural activity in the pyramidal tract may indeed play a significant role in regulating muscle force during walking. Pyramidal tract neurones display appreciable pace-by-pace variations in rate during steady walking and it is possible that it is these which are important. It may be that the over-all 'average' levels of muscle force appropriate to walking under different conditions are dictated by subcortical mechanisms but that by virtue of the pace-by-pace variations in their discharge pyramidal tract neurones participate in adaptively tuning the forces developed during individual paces. This possibility could be tested by provoking intentional small adjustments in limb trajectory and determining whether they are preceded by any corresponding changes in neuronal discharge rate.

Because stimulation of the medullary pyramid in acutely decerebrated cats can 'reset' the step cycle (Orlovsky, 1972) it has been proposed (see Armstrong & Drew, 1984*b*) that one important locomotor function of corticospinal neurones may be to regulate the timing of events within the step cycle. This speculation receives support

from the present work: brief stimulus trains often evoked contractions at times in the step cycle when the muscles are normally inactive and longer trains were capable of resetting the step cycle.

Stance is unduly prolonged immediately after pyramidectomy (Eidelberg & Yu, 1981) and activity in a substantial population of forelimb related pyramidal tract neurones was greatest in late stance (and least in swing) (Armstrong & Drew, 1984*b*). One particular timing function may therefore be to help to determine stance duration by controlling the time at which activity ceases in extensors. In this connexion it is of particular interest that the commonest triceps brachii response to microstimulation during stance was inhibition of the locomotor e.m.g. The latency of such responses was least in late stance.

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