ORIGINAL PAPER

Brigitte A. Lavoie · F. W. J. Cody · C. Capaday

Cortical control of human soleus muscle during volitional and postural activities studied using focal magnetic stimulation

Abstract The surface-recorded electromyographic (EMG) responses evoked in the ankle musculature by focal, transcranial, magnetic stimulation of the motor cortex were studied in healthy human subjects. Such soleus evoked motor responses (EMRs) were characterised over a wide range of background levels of motor activity and using different stimulus intensities. EMRs were recorded during predominantly (1) volitional and (2) postural tasks. In the former task subjects were seated and voluntarily produced prescribed levels of soleus activation by reference to a visual monitor of EMG. In the latter task subjects assumed standing postures without EMG feedback. Comparison of the EMRs of soleus, traditionally considered a slow anti-gravity extensor muscle, during these tasks was used to evaluate its cortical control in primarily volitional versus primarily postural activities. The form of soleus EMRs produced by single magnetic cortical stimuli comprised an initial (approx. 30 ms) increase and subsequent (approx. 50 ms) depression of EMG. Cortical stimulation could elicit substantial excitatory soleus EMG responses; for example, responses evoked by mild, magnetic stimuli (125% threshold for inducing a response in the relaxed muscle) as subjects exerted full voluntary plantarflexor effort averaged almost 20% of the maximum M-wave which could be elicited by an electrical stimulus to the posterior tibial nerve. Excitatory EMRs could be elicited in the voluntarily relaxed soleus muscle of the majority of subjects during sitting. The amplitude of soleus responses, induced by threshold stimuli for the relaxed state or approximately 125% threshold intensity, increased approximately linearly with background EMG over a wide range of volitional contraction levels. By contrast, there was no systematic change in the latency of excitatory soleus EMRs with increasing voluntary effort. The excitatory responses evoked in the voluntarily relaxed soleus of seated subjects by magnetic stimulation were regularly facilitated by incremental, voluntary contraction of the contralateral ankle extensors in a graded manner. However, such facilitation of responses was not observed when subjects voluntarily activated the muscle in which EMRs were elicited. The pattern of the responses elicited in soleus by magnetic stimulation during the postural task generally resembled that found during the volitional task. The amplitudes of excitatory soleus EMRs at a given stimulus intensity, obtained when subjects stood quietly, leaned forwards or stood on their toes to produce differing levels of ankle extensor contraction, increased with background EMG. Overall, the relationship between the size of cortically evoked soleus responses and the tonic level of motor activity, observed in individual subjects at matched stimulus intensities, did not consistently differ between postural and volitional tasks. The present results suggest that the motor cortex is potentially capable of exerting rapid regulation of the soleus muscle, and presumably other ankle extensors, not only when the muscle participates in volitional tasks but also when it is engaged in postural maintenance.

Key words Motor control · Motor cortex · Magnetic stimulation · Human

B. A. Lavoie · C. Capaday (✉)
Centre de Recherche en Neurobiologie, Hôpital de l'Enfant-Jésus, 1401 18th Street, Québec, (Qué), Canada, G1J 1Z4;
FAX no: (418) 649–5910, e-mail: ccapaday@vm1.ulaval.ca

F. W. J. Cody
School of Biological Sciences, University of Manchester, Manchester M13 9PT, UK

Introduction

It is generally held that, in man, muscles are subject to varying degrees of motor cortical control, depending on the extent of their engagement in "least automatic" versus "most automatic" movements, as categorised by Jackson (1931). According to this principle, the cortex exerts tight regulation over muscles involved in skilled, voluntary movements, as exemplified by digital manipulation, whilst the management of muscles responsible for postural maintenance and locomotion is delegated to

subcortical centres and reflex action. In keeping with this notion the distribution of cortical monosynaptic excitatory projections to alpha-motoneurones supplying the muscles of the primate hand is particularly dense and powerful (Phillips and Porter 1964; Clough et al. 1968; Phillips 1978) whilst H- and tonic stretch reflexes are best developed in classical anti-gravity muscles of the leg, e.g. soleus (see Matthews 1972).

Hitherto, most investigations of human motor cortical control, using recently developed electrical (Merton and Morton 1980) and magnetic (Barker et al. 1985) techniques for stimulation of the brain, have concerned muscles of the hand and arm. For these muscle groups, rapid and potent cortico-spinal connections have duly been demonstrated (Marsden et al. 1982; Hess et al. 1987). Comparative data for muscles of the leg, including slow ankle extensors, which are traditionally considered to be primarily postural, are fewer. So far, most investigations of the cortical control of the human soleus have been restricted to conditions of voluntary relaxation or low-level voluntary, tonic activation (Cowan et al. 1986; Advani and Ashby 1990; Ackermann et al. 1991; Brouwer and Ashby 1992; Dimitrijevic et al. 1992; Iles and Pisini 1992). However, more recently Kischka et al. (1993) have characterized the input/output relations over a much wider range of tonic activity and stimulus intensity.

The main objective of the present study was to determine whether the motor cortex is more directly involved in the regulation of the soleus activity during primarily volitional tasks versus primarily postural tasks. To this end, the effects of pre-existing activation level upon the size, latency and time course of cortically evoked soleus motor potentials, at different magnetic stimulus intensities, were systematically examined. Knowledge of how soleus responses to cortical volleys are modulated across the entire range of background contraction, and over a wide range of stimulus intensities, is crucial to interpreting studies of task-dependency of cortical influences during different motor activities (e.g. standing, running, jumping). This aspect of the present study complements that of Kischka et al. (1993) and was the basis of our approach to determining whether a similar degree of cortical regulation of the ankle musculature persists following the transition from deliberate volitional activation (during sitting) to a predominantly postural (during standing) task. Our investigation extends the studies of Ackermann et al. (1991), who have reported that soleus responses to magnetic cortical stimulation vary between postural activities (supine lying, quiet sitting, standing), although in those experiments differing unspecified levels of background motoneuronal excitability probably contributed.

In the event, our results demonstrate that the nature of the control exerted by the motor cortex over soleus qualitatively resembles that previously described for hand muscles, although the input-output relationship quantitatively differs in several important respects (see also Kischka et al. 1993). More importantly, the present findings suggest that the pathways mediating cortical influences upon the ankle extensors during voluntary, "less automatic", tasks remain operational during postural, "more automatic", activities. Some of the present findings have been published in preliminary form (Lavoie et al. 1994).

Materials and methods

The experiments were done on ten healthy subjects, eight men and two women, ranging in age between 23 and 47 years (32 ± 8.4 years, mean$\pm$SD). All subjects participated with their informed consent in accordance with the Declaration of Helsinki. Since the experiments required the application of many magnetic cortical stimuli, the number of subjects studied was restricted on safety grounds and particular care was taken to screen for any history of epilepsy or the presence of metal fragments in the eye or brain.

Experimental procedures

The electromyographic (EMG) responses evoked in the soleus muscle by transcranial magnetic stimulation of the motor cortex were investigated during (1) volitional activation of soleus muscle while sitting and (2) its contraction in the maintenance of standing postures. In the volitional task, subjects were comfortably seated with one leg partially outstretched. The angle of the knee joint was approximately 140° and that of the ankle joint was approximately 120°. Subjects were required to contract steadily the soleus of one ankle to generate and accurately sustain varying target levels of the muscle's maximal EMG activity, whilst maintaining the muscles of the other leg in a relaxed state. The active foot was positioned on a tilted platform against which subjects pushed by voluntarily plantarflexing the ankle. Subjects were provided with visual feedback of their contraction levels. An analogue voltmeter, calibrated so that a full-scale deflection of the needle corresponded to the subject's individual maximal soleus EMG (high-pass filtered 20 Hz, rectified, low-pass filtered 100 Hz), was placed in front of the subject at eye-level. The levels of target EMGs ranged from 0 to 100% of the maximum which subjects could generate whilst seated. In a number of experiments, subjects were required to produce matched, bilateral contractions of their soleus muscles. In the postural task, subjects stood upright and were required to produce several different maintained levels of soleus contraction. These levels were achieved by asking subjects to stand quietly with both the balls and heels of their feet in contact with the floor, to lean forwards by varying degrees or to stand "on their toes" by contracting their soleus muscles so as to raise their heels by requisite distances from the floor. Thus, active balancing was needed to maintain posture. No visual feedback of EMG level was provided to subjects during standing tasks. Instead, subjects were initially instructed to assume a given standing posture, which corresponded to a particular level of soleus EMG as monitored by the experimenters, and to maintain that posture throughout the trial. The range of EMG levels studied during standing was approximately 5–20% maximum and overlapped that occurring during the sitting task. Subjects switched to and fro between volitional (sitting) and postural (standing) tasks, whilst under each condition blocks of trials with different levels of EMG were interleaved in a pseudo-random manner. In control experiments, some subjects were asked to produce maximal standing ankle extensor contractions by attempting to raise their heels whilst gripping horizontal bars and powerfully contracting their biceps brachii muscles to provide resistance.

EMG recordings

Bipolar EMG recordings were obtained from two pairs of surface Ag-AgCl disc electrodes (diameter 0.9 cm, separation 3 cm) placed, respectively, over the bellies of soleus and tibialis anterior muscles. The electrodes were attached to the skin by O-rings of

double-sided adhesive film and firmly secured by overlying elasticated straps. The electrodes were shielded right up to their recording surfaces and connected to an optically isolated amplifier by a shielded twisted pair cable. The twisted pair cable reduces magnetic interference from the stimulating coil. EMG signals were amplified and filtered (20Hz-1 kHz) prior to sampling (4 kHz) by the computer analogue to digital (A/D) converter. EMG signals were also rectified and filtered (20–100 Hz) for sampling by a separate A/D channel and for providing visual feedback to subjects during the volitional task. Electrical stimuli (1-ms pulses) were applied to the tibial nerve in the popliteal fossa using a 1-cm roving cathode and a stimulus return electrode, which comprised a large metal plate covered with saline-wetted gauze, positioned just below the anterior aspect of the knee. Stimulus strength was adjusted to elicit a maximum M-wave in soleus, during quiet standing, to provide an index of motor activation capacity against which to compare cortically evoked motor responses. A previous study, using similar EMG recording methodology, has demonstrated that cross-talk between soleus and other ankle extensors is invariably less than ǀor equal to 10% (Capaday and Stein 1987). To test whether cɼoss-talk occurred between soleus and tibialis, the signals recorded from electrodes over the respective muscles were analysed. Fast Fourier transform (FFT) analysis was used to determine the spectral energy of the two sets of EMG signals occurring during the period (30–80 ms) expected for cortically evoked responses. In the presence of voluntary soleus contraction, there was little overlap of the frequency contents of the soleus and tibialis signals during this period; the spectral energy of the soleus and tibialis signals were, respectively, mainly greater than 70 Hz and less than 70 Hz. Since signals generated at distant sources typically contain lower frequency components, this finding suggests that under conditions of voluntary plantarflexion the cortically evoked responses recorded from soleus were largely uncontaminated by pick-up from tibialis anterior; additionally, any simultaneously elicited responses in tibialis anterior must have been relatively small.

Magnetic stimulation

Magnetic stimuli were applied over the scalp using a Cadwell MES-10 electromagnetic stimulator, of maximum magnetic field strength 2 T, with a double-D-shaped (16 cm×8 cm), coned focal coil. The coil was placed in contact with the scalp with the long axis of the intersection of its two loops pointing forwards, parallel to and approximately 0.5–1.0 cm lateral to the mid-line. The midpoint of the coil's intersection was aligned antero-posteriorly against the vertex. Stimulation employing this coil orientation was found to evoke the lowest threshold and most selective activation of the contralateral ankle musculature. Fine adjustments of coil position were routinely made for individual subjects to identify the optimal location. The coil was secured by a harness of straps which fastened beneath the subject's chin. Surface markings were drawn onto the scalp to serve as a reference grid against which the coil's position was regularly checked to ensure that no slippage occurred during the experiment. Additionally, the threshold for eliciting a soleus response under standard conditions (see below) was periodically measured and, if necessary, the coil's position was readjusted. These precautions ensured that evoked responses were highly stable and the coefficient of variation of the amplitude of the main excitatory wave was typically less than 2.

Stimulus pulses were of 70 μs duration and their intensity was measured as a percentage of the maximum current which could be discharged through the coil. Magnetic stimulus intensity was routinely referred to the threshold strength required to evoke a soleus response in the electromyographically quiescent muscle during sitting. The range of stimulus intensities relative to this threshold value was employed. The inter-stimulus interval varied between 4 and 7 s in a pseudorandom, equiprobable manner. Individual subjects participated in one recording session during which they received, on average, approximately 130 magnetic stimuli.

Data analysis

The data were acquired and reduced in real time. Means (typically eight trials) of the unrectified and rectified EMG responses evoked in both soleus and tibialis were computed at each combination of magnetic stimulus strength and level of soleus background activity, during volitional and postural tasks. The averaging period was 150 ms. In addition, a cumulative sum (CUSUM) was constructed from each averaged, rectified response by subtracting the background activity (50-ms period prior to magnetic stimulation) and then integrating the resulting waveform. Such CUSUMs provided the most sensitive method of identifying the latency of evoked potentials and whether responses began with increases or reductions in activity from pre-existing levels. Two measures of the size of cortically evoked EMG responses were obtained: firstly, the peak-to-peak amplitude of unrectified signals and, secondly, the integrated response (in millivolt seconds) computed from rectified means and calculated over the duration of the response as determined by visual inspection. An extremely high correlation was invariably found between these two measures and the peak-to-peak value was routinely adopted as the index of response size.

Results

### Basic pattern of cortically evoked soleus EMG responses

Figure 1 illustrates the general form of EMG responses evoked in the soleus muscle of a healthy, seated subject by transcranial magnetic stimulation over the leg area of the contralateral motor cortex. Stimulus intensity was adjusted to be at threshold for eliciting responses in the relaxed muscle.

Under conditions of voluntary relaxation, small compound action potentials, commencing at about 32 ms following stimulation and lasting some 20 ms, are evident in the unrectified (Fig. 1A) and rectified (Fig. 1B) EMG records. Figure 1D–I shows the effects of voluntary, unilateral contraction of soleus upon the responses evoked at the same stimulus strength. At 50% maximum background contraction (Fig. 1D–F), there is a substantial increase in the amplitude of the excitatory response. A sustained period of depression of EMG, with virtual silencing of discharge, can now be seen to succeed the main excitatory event. A discussion of the neural mechanisms underlying the depression of activity following the excitatory response can be found in Roick et al. (1993) and Ziemann et al. (1993). Inspection of the CUSUM (Fig. 1F) indicates that the initial component of the evoked response remained excitatory and its onset latency was essentially unaffected by volitional contraction. A further increase in voluntary contraction, to the maximum level which the subject could attain during sitting, produced an additional enhancement of the excitatory potential (Fig. 1G–I), especially in its later waves, without any definite change in onset latency. As the amplitude (peak-to-peak, unrectified waves) of excitatory evoked motor responses (EMRs) increased so the variability of response size, measured as coefficient of variation, declined in an approximately hyperbolic manner.

As an index of the strength of activation of the soleus motoneuronal pool, EMRs elicited by cortical stimulation were compared to M-waves produced by electrical

Fig. 1A–I Averaged (eight trials) electromyographic responses evoked in the soleus muscle of a healthy subject by focal, transcranial magnetic stimulation over the contralateral motor cortex. Single stimuli were applied at time 50 ms. Stimulus intensity was at threshold for eliciting a response in the relaxed muscle. Responses were evoked in the relaxed, electromyographically silent muscle (**A–C**) and whilst the subject exerted 50% maximum voluntary contraction (*MVC*) (**D–F**) and maximum voluntary contraction (**G–I**). Unrectified (**A,D,G**) and rectified (**B,E,H**) means and CUSUMs (**C,F,I**) are shown. The standard deviations of unrectified means and CUSUMs are indicated by the *dotted traces*. The amplitude scales of **A** and **B** (relaxed condition) differ from the corresponding ones for responses elicited during background contraction

A

B

Threshold ○
Threshold x 1.25 ✕
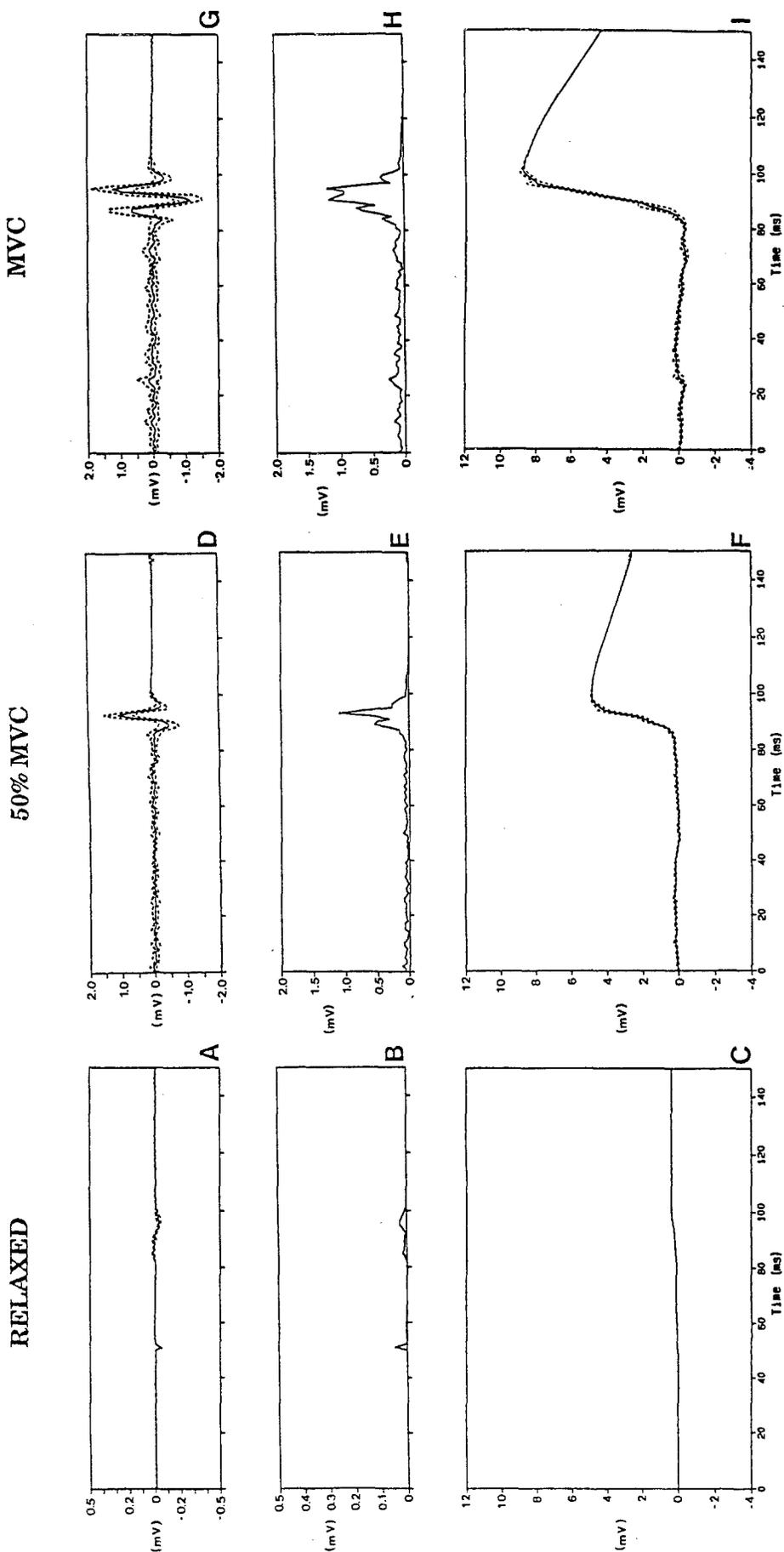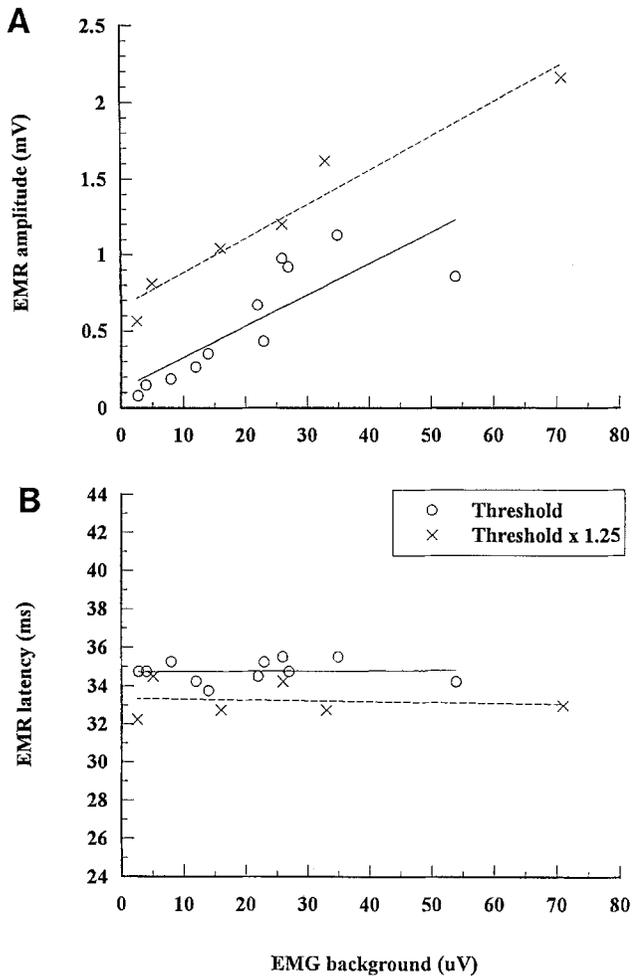
EMG background (uV)

Fig. 2 A The relationship between soleus excitatory evoked motor response (EMR) amplitude (peak-to-peak) and EMG background level, for a different subject to that in Fig. 1; B the relationship between EMR latency and EMG background. The maximum EMG level which the subject could voluntarily generate during sitting was 71 µV. In each graph, data obtained using stimuli of threshold intensity (*open circles, solid line*) and 125% threshold intensity (*crosses, dashed lines*) are separately plotted. The slopes of the amplitude-background relationships for threshold and 125% threshold intensities are, respectively, 0.020 and 0.022 mV/µV (r values 0.82 and 0.97) whilst the corresponding y-intercepts are 0.12 and 0.66 µV. The slopes of the latency-background relationships are 0.002 and –0.004 ms/µV (r values 0.04 and –0.11) and the corresponding y-intercepts are 34.7 and 33.4 ms

stimulation of the posterior tibial nerve. The amplitude of the EMRs, under conditions of maximal voluntary contraction and at stimulus intensity 125% threshold, were on average 17% of the maximal M-wave amplitude (n=7).

Figure 2 shows typical results of the influence of graded levels of voluntary, unilateral, background contraction upon the responses induced in soleus by magnetic stimuli of two strengths. At these two stimulus intensities, threshold and 125% threshold for eliciting responses in the relaxed muscle, the amplitudes of the excitatory EMRs increase approximately linearly with background contraction over the entire range of activation levels (Fig. 2A). However, no systematic alterations in onset la-

tency (Fig. 2B), which varies by several milliseconds between trials, are evident. Significant r values ($P<0.02$) were obtained in all subjects for the response amplitude-EMG relationships at the two stimulus strengths. By contrast, at neither stimulus intensity was the r value of the EMR latency-EMG background relationship significant ($P>0.05$). However, it may be possible that the latency decreases by some 3 ms in going from the relaxed state to the slightly contracted state (Kischka et al. 1993). The principle effect of increasing stimulus strength from threshold to 125% threshold, observed in four individual subjects, was to increase the y intercept of the EMR amplitude-EMG background relationship (paired t-test, $P=0.05$), whilst the slope was not significantly altered (paired t-test, $P>0.05$).

Influence of voluntary contraction of contralateral ankle extensors on cortically evoked soleus responses

To investigate whether volitional contraction of the contralateral ankle extensor muscles had a facilitatory action on excitatory soleus EMRs, responses were elicited whilst subjects exerted varying degrees of plantarflexor effort with the opposite foot. EMRs were recorded both from soleus muscles, which were themselves fully relaxed, and from muscles, which were voluntarily activated. The histograms of Fig. 3A show the mean amplitudes of normalised EMRs elicited in relaxed soleus muscles, in four individuals, when subjects either maintained the opposite ankle muscles in a relaxed state or produced small (approximately 10% maximum voluntary concraction, MVC), medium (50% MVC) or large (100% MVC) degrees of contralateral plantarflexion. The mean size of excitatory soleus EMRs recorded from relaxed muscles, elicited by stimuli of constant intensity, increased with the level of contralateral activation and more than doubled for the strongest contractions tested (Fig. 3A). Statistical analysis indicated that the amplitudes of EMRs elicited during maximal contraction of the contralateral ankle extensors significantly exceeded those obtained under conditions of contralateral relaxation (n=4, $P<0.05$, paired t-test). Thus, contralateral contraction had a clear facilitatory effect upon EMRs induced in relaxed soleus muscles. An example of such pronounced enhancement of soleus EMRs is illustrated in Fig. 3B, which superimposes the averaged, unrectified EMRs recorded from a subject's quiescent soleus under contralateral conditions of relaxation (*solid trace*) and strong plantarflexor effort (*dashed trace*). In contrast to these facilitatory effects upon soleus EMRs recorded from relaxed muscles, contralateral contraction had no definite influence upon responses elicited in muscles which were voluntarily activated. Figure 3C plots the relationship between soleus EMR amplitude and the background EMG level of the muscle from which recordings were made whilst a subject exerted differing levels of unilateral (*filled symbols*) or matched bilateral (*open symbols*) voluntary contraction. Data points corresponding to re-

102
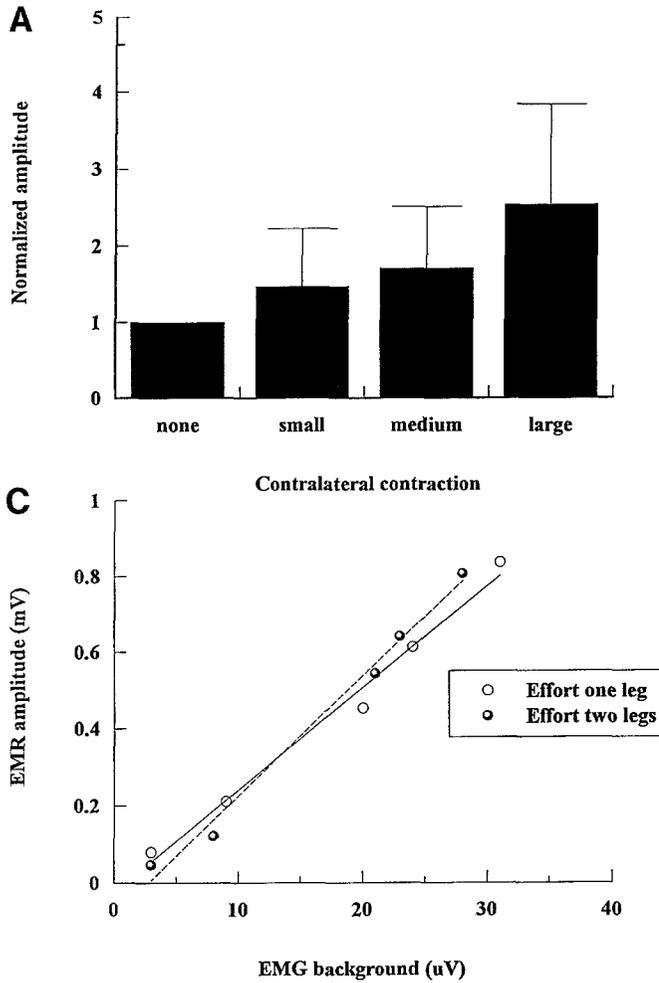
Fig. 3A–C The influence of voluntary contraction of the contralateral ankle extensors upon soleus evoked motor responses (EMRs). A The mean (+SD) amplitude (peak-to-peak) of excitatory EMRs elicited in the relaxed soleus muscles of four subjects, normalized to response sizes in the absence of contraction of the contralateral ankle musculature, are plotted for different strengths of voluntary contralateral activation. Stimulus intensity of magnetic shocks was 125% threshold for evoking a response in the quiescent soleus during a state of contralateral relaxation. Small, medium and large activation levels of the contralateral ankle extensors correspond, respectively, to approximately 10%, 50% and 100% of a subject's individual maximum voluntary contraction. B An example of the facilitatory effect of contralateral contraction in the unrectified, averaged (eight trials) records of soleus EMRs. The solid trace represents the EMR evoked in a relaxed soleus muscle of a subject in the absence of contralateral contraction. The EMR elicited in the relaxed soleus whilst the subject maintained a maximal volitional contralateral plantarflexor contraction is shown by the dashed trace. Stimuli were applied at 50 ms and were of 125% threshold intensity for eliciting a response when there was bilateral relaxation. C The relationships between EMR amplitude and EMG background level in the soleus muscle from which recordings were made are plotted in the presence (closed symbols, dashed line) and absence (open symbols, solid line) of voluntary contralateral plantarflexor effort. In the former condition, the subject attempted to maintain matched levels of bilateral contraction. Points corresponding to EMRs recorded from relaxed soleus muscles, such as in A and B, have been omitted. The maximum soleus EMG level voluntarily generated by this subject during sitting was 28 μV. The slopes of the relationships in the presence and absence of contralateral contraction are, respectively, 0.031 and 0.027 mV/μV (r values 0.995 and 0.993) and y-intercepts are −0.087 and −0.026 mV
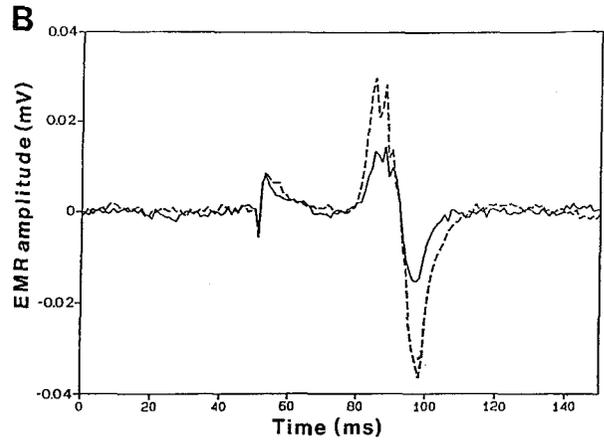
sponses obtained from the quiescent muscle have been excluded from this plot. Whilst EMR amplitudes are well correlated with background EMG for both conditions of unilateral ($r=0.99$, $P<0.01$) and bilateral ($r=0.99$, $P<0.01$) contraction, the relationships are quantitatively rather similar and there is considerable overlap of data points. Comparable findings were obtained in each of five other subjects studied. Statistical comparison of the relationships between EMR amplitude and background EMG under conditions of unilateral versus bilateral contraction indicated that neither the slopes nor y intercepts differed ($n=6$, $P>0.05$, paired t-tests) according to whether the extensors of one or both ankles were voluntarily activated. Thus, the facilitatory effect of contralateral ankle extensor activation on the EMR of the ipsilateral relaxed soleus disappears when the latter is active. This is an important consideration when dealing with the issue of task-dependent cortical mechanisms, which is the subject of the next section.

Comparison of cortically evoked soleus responses during volitional versus postural tasks

The general pattern of responses elicited in soleus by magnetic stimulation of the contralateral motor cortex during standing resembled that previously described for sitting. Varying levels of tonic soleus EMG were achieved by subjects assuming different standing postures, i.e. quietly standing, leaning forwards and standing on their toes. Unlike the studies during sitting, subjects were not provided with visual feedback or any other knowledge of their soleus EMG; there was no direct conscious control of either the posture or the level of soleus activity. They adopted in their own way the posture instructed, in general terms, by the experimenter.
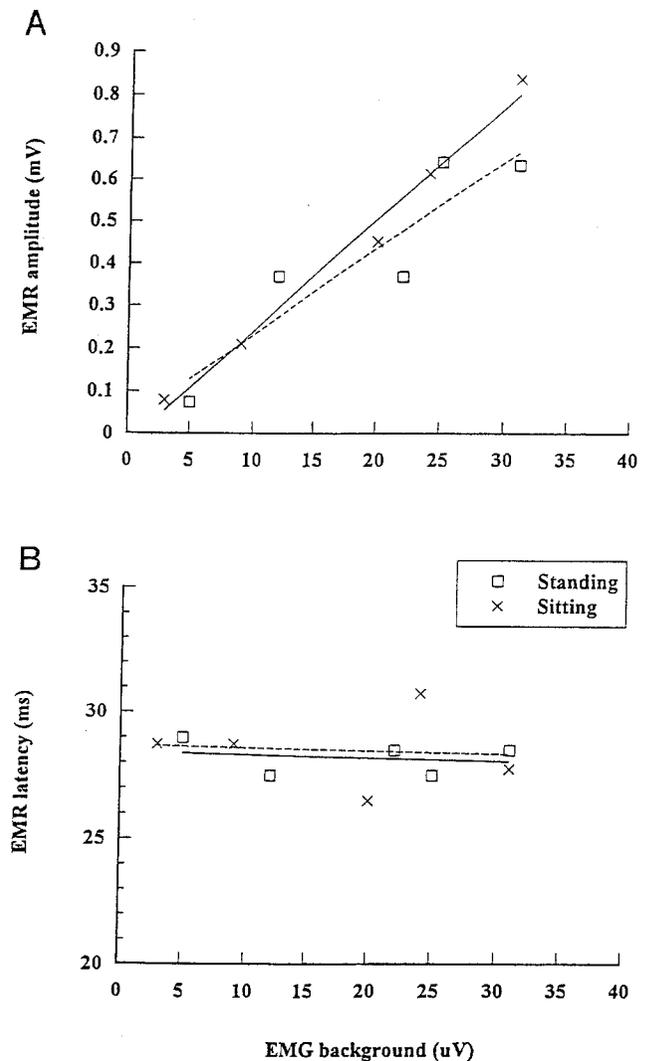
Figure 4A plots the relationship between the amplitude of the excitatory response, evoked at the same stimulus intensity (125% threshold for the relaxed muscle), and the level of background EMG (range 0–80% maximum) which was observed in one subject. A strong positive correlation exists ($r=0.91$, $P<0.01$). In six of the eight subjects studied, significant ($P<0.05$) positive cor-

A

B

A

B
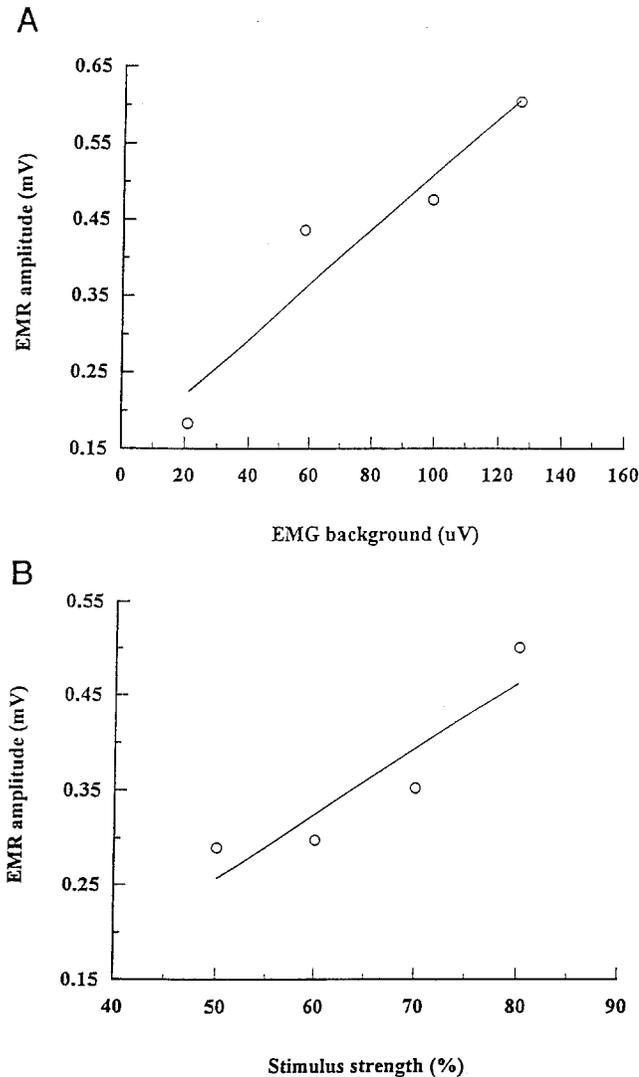
Fig. 4 A The relationship between soleus excitatory evoked motor response (EMR) amplitude (peak-to-peak) and EMG background level recorded in a standing subject is plotted. The EMG level recorded during maximal contraction was 130 μV. Stimulus intensity was 125% threshold for eliciting a response in the relaxed soleus muscle of the subject during sitting. The slope is 0.004 mV/μV (*r* value 0.95) and *y*-intercept is 0.15 mV. **B** The effect of stimulus intensity upon EMR amplitude, recorded in the same subject during quiet standing. The strength of magnetic shocks is expressed as a percentage of the maximal output of the stimulator. The correlation coefficient has a value of 0.91

Fig. 5 A The relationships between soleus excitatory evoked motor response (EMR) amplitude (peak-to-peak) and EMG background level are compared for a single subject during standing (*squares, dashed line*) and sitting (*crosses, solid line*). In the latter task, voluntary contraction was confined to the ankle musculature from which recordings were being made. The tonic EMG maxima for the two tasks were, respectively, 31 μV and 28 μV. Stimulus intensity was 125% threshold for eliciting responses in the relaxed soleus during sitting. The slopes of the relationships during standing and sitting are, respectively, 0.02 and 0.03 mV/μV (*r* values 0.92 and 0.99) and *y*-intercepts are 0.03 and –0.03 mV. **B** The corresponding EMR latency-EMR background relationships. The *r* values of the correlations for standing and sitting tasks are, respectively, –0.21 and –0.09 and the corresponding *y*-intercepts are 28.4 and 28.7 ms

relations were found between response amplitude and background activity as tonic EMG level increased to about 80% of the individual maximum. The synchronised motor discharges elicited by weak magnetic stimuli typically produced pronounced contractions of the ankle extensors, which, for example, during quiet standing were sufficiently powerful to lift a subject's body weight and cause the heel to be raised off the ground.

The amplitude of cortically evoked, excitatory soleus responses was also dependent on stimulus intensity. Figure 4B shows that the size of the responses, evoked in the same subject during quiet standing when background EMG was about 30% maximum, progressively increased

with stimulus strength. In five of six subjects tested significant (*P*<0.05) positive correlations between response size and stimulus intensity were obtained.

The responses evoked in soleus by magnetic cortical responses were compared, in eight subjects, during predominantly volitional (while sitting) and postural (several standing postures) activities. The voluntary task involved contraction of the soleus of one leg to generate prescribed, steady, target levels of EMG using visual feedback; thus, soleus was under direct "volitional" con-

trol. Standing tasks involved bilateral soleus contraction. They required active balancing, in the absence of visual EMG feedback or other knowledge of performance, so that soleus was operating in a more "postural" mode.

Figure 5 plots the relationships between the (1) amplitude and (2) latency of a subject's soleus excitatory EMRs, evoked at a given stimulus intensity, and background EMG during the voluntary and standing tasks. Stimulus intensity was standardised to 125% threshold for eliciting a response during quiet standing. Increasing levels of tonic EMG during the latter condition were obtained by requiring subjects to quietly stand, to lean forwards or to stand on their toes. Figure 5A indicates that for both the standing and the sitting conditions good correlations between EMR size and background soleus activity are present (r values, respectively, 0.92 and 0.99; $P<0.05$). However, the slopes of the regression lines are similar and there is considerable overlap of data points. Thus, there is no indication that the EMR amplitude-background EMG relationships differ between postural and voluntary tasks. Under neither condition was latency significantly correlated with background EMG activity (r values -0.21 and -0.09, $P>0.1$), nor were there any differences in onset latencies. Pair-wise statistical comparisons, in eight individual subjects, of the slopes and y intercepts of the EMR amplitude-background EMG relationships recorded during standing and sitting indicated that neither parameter differed significantly between the tasks (paired t-tests, $P>0.05$).

The different standing postures employed to generate a wide range of background EMG levels might be suggested to involve varying degrees of postural versus volitional bias. In particular, the act of standing on the toes, by intentionally contracting ankle extensors to raise the heels, would seem to be inherently more volitional in nature than quiet standing or slightly leaning forwards, which are more automatic postures. Therefore, separate comparisons were made in the eight subjects of response amplitudes evoked, at matched tonic EMG levels, under conditions of sitting versus quiet standing/leaning forwards. Again, no consistent difference emerged between the tasks. In two subjects the responses were significantly (paired t-test, $P<0.05$) greater during sitting and in two subjects during standing, whilst no significant differences were found for the remaining four subjects.

Discussion

The main new finding reported in the present paper is that the EMRs of the soleus are tied to the background level of α-motoneuron pool activity in the same way during predominantly voluntary versus predominantly postural motor tasks. This finding implies that the descending tracts and spinal circuitry whereby cortical control is exerted during volitional activation of the ankle muscles continue to be operational during postural tasks; and may thus contribute to postural maintenance and adjustments. A discussion of the characteristics and potential neural mechanisms of the cortical regulation of soleus is given below. This is followed by an assessment of the possible strengths and limitations of the present approach in determining differences in the contribution of the cerebral cortex to voluntary versus postural motor activities.

The characteristics of cortical control of soleus

The characteristics of cortical control of the human soleus muscles, revealed in the present experiments using focal magnetic stimulation, qualitatively resemble those previously described for hand muscles (see Hess et al. 1987), whilst quantitatively differing in a number of key respects. The cortically evoked soleus responses were of appreciable size. Under conditions of strong background contraction even weak cortical shocks (125% threshold) produced EMRs whose peak-to-peak amplitude approached 20% of that of the maximal M-wave, a value which may tend to underestimate the potency of descending excitation, since EMRs are less synchronised waves. The present findings of powerful cortico-spinal excitation of soleus contrasts with some earlier reports in which only weak facilitatory actions could be demonstrated (Advani and Ashby 1990; Brouwer and Ashby 1992). We suspect that this discrepancy is mainly due to more effective focal stimulation of the leg area having been applied in the present experiments by the use of a large coned coil, as opposed to a circular non-focal coil as was used in previous studies. This view is supported by the recent finding of several groups that the sizes of responses elicited in lower limb muscles did not differ significantly from those evoked in upper limb muscles provided shocks were applied by suitable magnetic stimulating coils (Ackermann et al. 1991; Dimitrijevic et al. 1992; Kischka et al. 1993).

The amplitude of soleus responses, elicited by weak magnetic stimuli, increased progressively with background EMG over virtually the full range of voluntary contraction strengths, as was also shown by Kischka et al. (1993) for contractions strengths of up to 60%. In the case of hand muscles, however, although the evoked muscle potentials were considerably enhanced by small amounts of contraction, a saturation of response size occurred at around 5% maximal force (Hess et al. 1987). We suggest that the more extended gradation of cortically evoked soleus responses with increasing tonic activity probably arises from two related causes. First, the amplitudes of excitatory postsynaptic potenials (EPSPs) generated in human soleus motoneurones by cortical shocks are probably comparatively small, as has been shown for lower limb motoneurones in monkeys using intracellular recordings (Jankowska et al. 1975). Since small EPSPs are individually less likely than large ones to bring motoneuronal membranes to firing threshold, there is greater opportunity for progressive summation in regulating discharge. Second, the relative importance of rate modulation versus recruitment in force control probably differs

between hand muscles and soleus. The experiments of Milner-Brown and colleagues (Milner-Brown et al. 1973a,b) indicate that in small hand muscles, with limited numbers of motor units, many units are recruited early in contraction and thereafter rate coding produces increases in force. Although comparable data for human soleus are lacking, cat studies suggest that sequential recruitment of motor units is the predominant mechanism of incremental force control in this muscle (Grillner and Udo 1971). In this case, at any given level of contraction a proportionately larger fraction of the large soleus motor unit population would be available for activation by cortico-spinal inputs. We believe that these factors underlie basic differences in the modes of operation of soleus and hand muscle motor pools. In this context, soleus H-reflexes are, like their cortical EMRs, strongly graded over a wide range of background contraction levels (Gottlieb et al. 1970; Capaday and Stein 1986, 1987). As will be discussed below, muscles such as the soleus and biceps brachii (Kischka et al. 1993) may in fact be the most appropriate for studies of cortical task dependence, because they possess graded input/output properties.

The enhancement of soleus EMRs produced by voluntary homonymous activation was not accompanied by an increase in cortically evoked responses in tibialis anterior. Palpation indicated that no corresponding increase in antagonist contraction occurred, whilst spectral analysis confirmed that the signals recorded by tibialis anterior electrodes arose predominantly from electrotonic spread of activity from the ankle extensors. Thus, the EMR recorded from the soleus were essentially free of artefactual cross-talk components coming from the flexor compartment in the leg.

We observed that voluntary contraction of the contralateral ankle extensors had a genuine facilitatory effect upon responses evoked in the relaxed soleus by weak magnetic stimuli. A comparable effect has been noted for abductor digiti minimi (Hess et al. 1987). In the case of soleus, such facilitation disappeared when the muscle in which EMRs were elicited was itself voluntarily activated; thus, the facilitatory effect of contralateral soleus contraction, whether operating at cortical or spinal levels, was relatively weak. It would not appear capable of significantly contributing to bilateral contractions of the ankle extensors during standing, an important consideration in studies of motor cortical task dependence.

Cortical control of soleus during volitional and postural tasks

The general pattern of the responses evoked in soleus by magnetic cortical stimulation during bipedal standing resembled that observed when subjects voluntarily produced unilateral contraction of the muscle. Furthermore, quantitative comparison of the responses elicited, across all subjects, under these two conditions showed that neither the amplitudes nor latencies of the primary excitatory components, for matched stimulus intensities and background contraction strengths, significantly differed between voluntary activity and standing. This finding was equally true when differing standing tasks (e.g. quiet standing/leaning forwards versus voluntary activity), which probably require differing levels of conscious, willed control, were considered. For example, the quiet standing task is certainly an essentially postural task requiring little willed control, whereas voluntary exertion of the same level of activity requires direct conscious attention to the task. Yet, there was no difference in the size or latency of the EMRs between these two tasks. These observations demonstrate that the cortical neurones, descending pathways and segmental circuitry whereby the evoked responses are mediated remain operational during both volitional and postural tasks. Additionally, these results suggest that the motor cortex is potentially capable of exerting a comparable degree of regulation of soleus when the muscle participates in both "less" and "more automatic" activities.

These conclusions may be contrary to intuitive expectation, since it might be assumed that the motor cortex would be more powerfully involved in volitional tasks. Therefore, possible technical and physiological explanations for the similarity of cortically evoked responses during voluntary activity and standing must be considered. The first possibility is that magnetic stimulation is not an adequate method to demonstrate subtle alterations in cortico-spinal excitability. If, for instance, magnetic stimulation were directly to excite deep cortico-spinal fibres from the ankle area, changes in the excitability of cortical neurones would go undetected. However, Edgley et al. (1990) have reported that, whilst electromagnetic stimulation of the hand area of monkeys produced activation of cortical neurones both directly (probably at the initial segment) and indirectly (trans-synanaptically), there was no indication that it produced distant stimulation of cortico-spinal fibres. Indeed, the present balance of evidence is that cortical excitability influences EMRs, whether they result from D (direct) waves, I (indirect) waves or both (see Burke et al. 1993; Kujirai et al. 1993; Baker et al. 1994). In accord with this view, there have been reports of task-related changes in magnetically evoked EMRs of hand muscles (Datta et al. 1989, Flament et al. 1993). Alternatively, if cortico-spinal actions on soleus motoneurones are mainly mediated by spinal interneurones which receive convergent inputs from several central and peripheral sources, a reduction in cortical drive might be offset by an increase in interneuronal excitability of reflex afferent origin, so that the net cortically evoked response remained essentially constant. In this context, it may be possible to demonstrate clearer differential cortical actions upon the ankle muscles when they are involved in other types of movement. Indeed, the recent demonstration that early facilitation of soleus H-reflexes by conditioning cortical magnetic stimuli varied during agonist contraction versus agonist-antagonist co-contraction (Nielsen et al. 1993) suggests that magnetic stimulation can provide a sensitive method of testing cortical control of these muscles.

106

In contrast to the above studies which reported that the level of cortical excitability influenced the amplitude of EMRs, Maertens de Noordhoot et al. (1992) were unable to demonstrate an added effect of the level of cortical excitability on tibialis anterior EMRs produced by magnetic stimulation. The reason(s) for this is not clear; perhaps it may be due to the different orientation of cortico-spinal neurons in the ankle area of the motor cortex relative to the stimulating coil compared with that of the corticospinal neurons in the forelimb area of the motor cortex. Whatever the reason(s) for the discrepancy, a lack of effect of the level of cortical excitability on the amplitude of EMRs may explain why we did not observe a difference in the size of the EMRs between the mainly volitional versus the mainly postural tasks we investigated (see further arguments below). The findings of Mazzocchio et al. (1994) are also relevant to the present discussion. This study, in fact, strongly supports the idea that magnetic stimuli with a figure-of-eight coil (as well as a round coil) produce EMRs that depend on the excitability of the motor cortex. However, one of the subtle findings of that study, was that the figure-of-eight coil produced in three of seven subjects an additional earlier facilitation (conditioning-testing intervals of −3 to −5 ms vs the usual −1 to −3 ms) of the wrist flexor H-reflex than the round coil. They interpreted this early facilitation as a D wave, and reported that it was not modified by the excitability of the motor cortex, unlike the later facilitation. The extent to which our measurements reflect the "early" versus the more usual "later" phase of cortical facilitation cannot be determined with any certainty. However, since nearly all studies report that magnetic stimulation produces mainly trans-synaptic I waves (or activation of the initial segment of pyramidal tract cells) and that these are influenced by the level of cortical excitability, our EMRs must, at least in part, be due to I waves (or activation of the initial segment) and hence potentially modifiable by the level of cortical excitability.

One of the strengths of the present study was to carefully determine input/output relations over a wide range of parameters. This allows an assessment of the likelihood of various possibilities, such as whether or not occlusion within the cortico-spinal system occurred. Thus, it seems that if there was a genuine difference in motor cortical excitability it should have been detected, because the stimulus intensity of 125% threshold is nowhere near the saturation level, as can be seen in the graphs of Figs. 2 and 4. The EMR grows as a function of background EMG at 125% of threshold, and also as a function of stimulus intensity (up to 1.6×threshold in Fig. 4). There is thus ample range available for the EMR to increase as a result of a change in cortical excitability, especially at low EMG levels and 125% threshold stimulus intensity. The possibility of occlusion at the cortical level between the effects of the magnetic stimulus and ongoing activity of the cortico-spinal cells (for example if the motor cortex were more engaged in the volitional task) thus seems unlikely. The input/output measurements such as those of Figs. 2 and 4 strongly suggest that we were not operating anywhere near saturation of the cortico-spinal system. Therefore, a task-dependent increase in excitability within this system, if it occurred, would have been observed as an upward displacement of the EMR versus EMG relation, as in Fig. 2.

In summary, whatever the precise neural mechanisms involved, the main conclusion of our study is that the motor cortex seems equally well linked to the spinal motor circuits in mainly volitional versus mainly postural motor tasks. Indeed, several independent lines of evidence provide circumstantial support for the idea that the motor cortex can play a direct role in modulating the activity of ankle muscles during postural maintenance. Nashner (1976) has demonstrated that when quietly standing subjects are displaced, to throw them off balance, the most prominent adaptive, corrective EMG responses in ankle extensors occur at a latency which is sufficiently long to be compatible with cortical action. Such responses are absent in patients with cerebellar damage (Nashner 1978), including lesions of the neocerebellum, whose outputs are largely directed to the motor cortex. Additionally, numerous reports have stressed the importance of visually triggered corrective reactions in postural regulation (reviewed by Lacour et al. 1978), which are likely to be channelled via the motor cortex.

Overall, we believe that, contrary to earlier views that the major role of the cortico-spinal system in regulating soleus is in exerting a rather non-specific inhibitory action to suppress anti-gravity mechanisms (Preston et al. 1967), the motor cortex provides an important source of excitatory drive during soleus contractions occurring both in willed movement and postural maintenance. Elucidation of the details of motor cortical control in postural reactions should be a challenging and fruitful avenue of future research.

References

Ackermann H, Scholz E, Koehler W, Dichgans J (1991) Influence of posture and voluntary background contraction upon compound muscle action potentials from anterior tibial and soleus muscle following transcranial magnetic stimulation. Electroencephalogr Clin Neurophysiol 81: 71–80

Advani A, Ashby P (1990) Corticospinal control of soleus motoneurons in man. Can J Physiol Pharm 68: 1231–1235

Baker SN, Olivier E, Lemon RN (1994) Recording an identified pyramidal volley evoked by trancranial magnetic stimulation in a conscius macaque monkey. Exp Brain Res 99: 529–532

Barker AT, Freeston IL, Jalinous R, Merton PA, Morton HB (1985) Magnetic stimulation of the human brain (abstract). J Physiol (Lond) 369: 3P

Brouwer R, Ashby P (1992) Corticospinal projections to lower limb motoneurons in man. Exp Brain Res 89: 649–654

Burke D, Hicks R, Gandevia SC, Stephen J, Woodforth I, Crawford M (1993) Direct comparison of corticospinal volleys in human subjects to transcranial magnetic and electrical stimulation. J Physiol (Lond) 470: 383–393

Capaday C, Stein RB (1986) Amplitude modulation of the soleus H-reflex in the human during walking and standing. J Neurosci 6: 1308–1313

Capaday C, Stein RB (1987) Difference in the amplitude of the human soleus H-reflex during walking and running. J Physiol (Lond) 392: 513–522

Clough JFM, Kernell D, Phillips CG (1968) The distribution of monosynaptic excitation from the pyramidal tract and from primary spindle afferents to motoneurones of the baboon's hand and forearm. J Physiol (Lond) 198: 145–166

Cowan JMA, Day BL, Marsden CD, Rothwell JC (1986) The effects of percutaneous motor cortex stimulation on H reflexes in muscles of the arm and leg in intact man. J Physiol (Lond) 377: 333–347

Datta AK, Harrison LM, Stephens JA (1989) Task-dependent changes in the size of response to magnetic brain stimulation in human first dorsal interosseous muscle. J Physiol (Lond) 418: 13–23

Dimitrijevic MR, Kofler M, McKay WB, Sherwood AM, Van der Linden C, Lissens MA (1992) Early and late lower limb motor evoked potentials elicited by transcranial magnetic motor cortex stimulation. Electroencephalogr Clin Neurophysiol 85: 365–373

Edgley SA, Eyre JA, Lemon RN, Miller S (1990) Excitation of the cortico-spinal tract by electromagnetic and electrical stimulation of the scalp in the macaque monkey. J Physiol (Lond) 425: 301–320

Flament D, Goldsmith P, Buckley CJ, Lemon RN (1993) Tak dependence of responses in first dorsal interosseous muscle to magnetic brain stimulation in man. J Physiol (Lond) 464: 361–378

Grillner S, Udo M (1971) Recruitment in the tonic stretch reflex. Acta Physiol Scand 81: 571–573

Gottlieb GL, Agarwal GC, Stark L (1970) Interactions between voluntary and postural mechanisms of the human motor system. J Neurophysiol 33: 365–381

Hess CW, Mills KR, Murray NMF (1987) Responses in small hand muscles from magnetic stimulation of the human brain. J Physiol (Lond) 388: 397–419

Iles JF, Pisini JV (1992) Cortical modulation of transmission in spinal reflex pathways of man. J Physiol (Lond) 455: 425–446

Jackson JH (1931) Selected writings of John Hughlings Jackson. In: Taylor J (ed) Hodder and Stoughton, London

Jankowska E, Padel Y, Tanaka R (1975) Projections of pyramidal tract cells to alpha-motoneurones innervating hindlimb muscles in the monkey. J Physiol (Lond) 249: 637–667

Kischka U, Fajfr R, Fellenberg T, Hess CW (1993) Facilitation of motor evoked potentials from magnetic brain stimulation in man: a comparitive study of different target muscles. J Clin Neurophysiol 10: 505–512

Kujirai T, Caramia MD, Rothwell JC, Day BL, Thompson PD, Ferbert A, Wroe S, Asselman P, Marsden CD (1993) Corticocortical inhibition in human motor cortex. J Physiol (Lond) 471: 501–519

Lacour M, Vidal PP, Xerri C (1978) Dynamic characteristics of vestibular and visual control of rapid postural adjustments. In:

Desmedt JE (ed) Motor control mechanisms in health and disease. Raven, New York, pp 589–606

Lavoie BA, Cody FWJ, Capaday C (1994) Cortical control of human soleus during volitional and postural tasks studied using transcranial magnetic stimulation (abstract). J Physiol (Lond) 475: 38–39P

Maertens de Noordhoot A, Pepin JL, Gerard P, Delwaide PJ (1992) Facilitation of responses to motor cortex stimulation: effects of voluntary isometeic contraction. Ann Neurol 32: 365–370

Marsden CD, Merton PA, Morton HB (1982) Percutaneous stimulation of spinal cord and brain; pyramidal tract conduction velocities in man (abstract). J Physiol (Lond) 328: 6P

Matthews PBC (1972) Mammalian muscle receptors and their central actions. Arnold, London

Mazzocchio R, Rothwell JC, Day BL, Thompson PD (1994) Effect of tonic voluntary activity on the exitability human motor cortex. J Physiol (Lond) 474: 261–267

Merton PA, Morton HB (1980) Stimulation of the cerebral cortex in the intact human subject. Nature 285: 287

Milner-Brown HS, Stein RB, Yemm R (1973a) The orderly recruitment of human motor units during voluntary isometric contractions. J Physiol (Lond) 230: 359–370

Milner-Brown HS, Stein RB, Yemm R (1973b) Changes in firing rate of human motor units during linearly changing voluntary contractions. J Physiol (Lond) 230: 371–390

Nashner LM (1976) Adapting reflexes controlling the human posture. Exp Brain Res 26: 59–72

Nashner LM (1978) Analysis of movement control in man using the movable platform. In: Desmedt JE (ed) Motor control mechanisms in health and disease. Raven, New York, pp 607–620

Nielsen J, Petersen N, Deuschl G, Ballegaard M (1993) Task-related changes in the effect of magnetic brain stimulation on spinal neurones in man. J Physiol (Lond) 471: 223–243

Phillips CG (1978) Significance of the monosynaptic cortical projection to spinal motoneurones in primates. In: Desmedt JE (ed) Motor control mechanisms in health and disease. Raven, New York, pp 1–9

Phillips CG, Porter R (1964) The pyramidal projection to motoneurones of some muscle groups of the baboon's forelimb. Prog Brain Res 12: 222–242

Preston JB, Shende MC, Uemura K (1967) The motor cortex-pyramidal system: patterns of facilitation and inhibition on motoneurones innervating limb musculature of the cat and baboon and their possible adaptive significance. In: Yahr M, Purpura D (eds) Neurophysiological basis of normal and abnormal motor activities. Raven, Hewlett, pp 61–74

Roick H, Geisen von HJ, Benecke R (1993) On the origin of post-excitatory inhibition seen after transcranial magnetic brain stimulation in awake human subjects. Exp Brain Res 94: 489–498

Ziemann U, Netz J, Szelény A, Hömberg V (1993) Spinal and supraspinal mechanisms contribute to the silent period in the contracting soleus muscle after transcranial magnetic stimulation of human motor cortex. Neurosci Lett 156: 167–171