ORIGINAL COMMUNICATION

Philipp Diehl
Uta Kliesch
Volker Dietz
Armin Curt

Impaired facilitation of motor evoked potentials in incomplete spinal cord injury

■ **Abstract** *Objectives* To improve the diagnosis of damaged spinal motor pathways in incomplete spinal cord injury (iSCI) by assessing the facilitation of lower limbs motor evoked potentials (MEP). *Methods* Control subjects (n = 12) and iSCI patients (n = 21) performed static and dynamic isometric foot dorsiflexions. MEPs induced by transcranial magnetic stimulation and EMG background of tibialis anterior muscle (TA) were analyzed. Static and dynamic muscle activation was performed at comparable levels of maximal voluntary contraction (MVC). The influence of the motor tasks on the excitability and facilitation of MEPs was compared between controls and iSCI patients. *Results* In the controls an increased facilitation of TA MEP at lower levels of dynamic compared with static activation (10–20 % MVC) could be shown. At matched EMG background level the MEP responses were significantly increased. In the iSCI patients at a comparable level of TA activation the MEP responses were significantly reduced and 3 different patterns of MEP responses could be distinguished: i) preserved increment of TA MEP in the dynamic motor task, ii) un-changed MEP size in the dynamic and static motor task, and iii) elic-itable MEPs in the dynamic motor task, which were abolished in the static motor task. *Conclusions* Static and dynamic motor tasks have different effects on TA MEP facili-tation. The task-dependent modu-lation of TA MEPs is comparable to that described for upper limb mus-cles. Complementary to the MEP delay this approach allows for an estimation of the severity of spinal tract damage. The task-dependent modulation of TA MEPs is an addi-tional diagnostic tool to improve the assessment and monitoring of motor function in iSCI.

■ **Key words** transcranial magnetic stimulation · task-dependent facilitation · tibialis anterior · spinal cord injury

Ph. Diehl · U. Kliesch · V. Dietz ·
A. Curt, MD (✉)
Spinal Cord Injury Center
University Hospital Balgrist
Forchstrasse 340
8008 Zürich, Switzerland
Tel.: +41-1/3863945
E-Mail: Armin.Curt@balgrist.ch

Introduction

The stimulation of the motor cortex using transcranial magnetic stimulation (TMS) allows for a non-invasive, painless and safe assessment of human central and pe-ripheral motor pathways [19, 36]. Voluntary contraction of a target muscle at the time of the stimulation facili-tates the motor evoked potential (MEP) compared with the resting state. This facilitation is represented by a sig-nificant increase of the MEP amplitude, shortening of the MEP latency, and a decrease of the stimulation threshold [3, 8, 27, 37, 42, 44]. Besides the voluntary con-traction of a target muscle, a facilitation of the MEP can also be achieved by other maneuvers such as activation of the contralateral limb, or even by imaging or observ-ing a movement [22].

In clinical practice, a voluntary contraction of the tar-get muscle is the most commonly applied technique during MEP assessment to facilitate responses. However, the relationship between the strength of voluntary con-traction of the target muscle and the effect of MEP facil-itation is complex and is influenced at both spinal-seg-mental and supraspinal levels [14, 24, 37]. The different neuronal mechanisms, which are assumed to influence the facilitation, have been extensively addressed in prox-

imal and distal upper limb muscles [13, 35]. During simple movements of proximal upper limb muscles (deltoid muscle) increased MEP amplitudes during dynamic contractions were found, while the distal hand muscles did not show a comparable facilitation [1]. However, during a precision grip in contrast to a power grip (at similar background EMG level) a task-dependent facilitation in intrinsic hand muscles occurs [16]. A task-dependent MEP facilitation could also be demonstrated in movements using both task specific and unspecific activation of distal and proximal upper limb muscles with an enhanced supraspinal control during a precision task in contrast to a postural activation [39]. According to animal studies the different input-output relations depend on the amount and distribution of direct cortico-motoneuronal (CM) connections to upper limb muscles. The density of cortico-motoneuronal connections is assumed to decline from distal to proximal muscles [33]. In the lower limbs for the tibialis anterior (TA) muscle a similar amount of CM connections can be assumed [2, 26, 32]. In spinal lesions the assessment of MEPs focuses on the preserved excitability and the delay of the MEP response. As the MEP amplitudes are highly variable they are of minor diagnostic value compared with the MEP latencies. However, it can be assumed that besides the delay of the MEP, changes in the MEP facilitation due to impaired spinal conductivity also occur. Therefore, the evaluation of MEP facilitation in iSCI patients could be a valuable diagnostic tool in assessing spinal motor pathways.

The present study focuses on the task-dependent facilitation of the TA by performing an isometric dorsiflexion of the foot during two different motor tasks: a controlled static versus a dynamic muscle activation. The aim of the study was: 1) to provide a paradigm that allows for the disclosure of different levels of lower limb muscle facilitation, and 2) to evaluate in iSCI patients if changes of task-dependent facilitation can be applied to expose different extents of spinal motor pathway impairment.

Methods

Control subjects and patients

The study was performed on 12 healthy volunteers (4 women, 8 men, mean age 26.8 years, range 20–31) and 21 patients with iSCI (8 women, 13 men, mean age 53.1 years, range 16–81). Exclusion criteria for participation in the experiment were cardiac pacemakers, neurological diseases and implanted ferromagnetic cranial devices. The neurological classification of the patients was performed according to the American Spinal Injuries Association (ASIA) [30]. All patients had a chronic iSCI (average 28.8 months after the spinal cord injury) and suffered from lower limb weakness due to spinal cord injury. The TA motor impairment was scored by a manual muscle test. The muscle force was scored from M0 (no contractile activity can be felt in the gravity eliminated position) to M5 (patient can hold the position against maximum resistance and through complete range of motion)

and reached a mean of M4.1 (range of M2 – M5) in the patient group. 15 patients had a medical cause of the spinal cord injury, while 6 patients had a traumatic etiology.

The study was approved by the local Ethics Committee of the University Hospital Balgrist and was performed in accordance with the Declaration of Helsinki. All patients and controls were instructed about the aims of the study and gave written informed consent.

Motor tasks

To achieve comparable inter-individual levels of activation, both motor tasks were performed using pre-defined levels of individual maximal voluntary contraction (MVC). MVC for each subject was determined by 4–6 times recording the torque of maximal voluntary foot dorsiflexion. The average of these values was used in the following measurements as the individual 100 % MVC. In the control subjects a recruitment curve of the influence of force generation was achieved by the performance of both motor tasks at 10, 20, 40 and 60 % of MVC. Five recordings were performed at each contraction level and motor task. In the iSCI patients, based on the findings of the control subjects MEP facilitation was studied at 20 % MVC.

Static motor task

The control subjects and patients were asked to perform an isometric static (i. e. an isometric-isotonic) contraction. The investigator had visual feedback about the actual force generation and gave instructions to the subject as to whether to reach or keep the required level of contraction. After the required contraction level was kept for a period of 2–4 sec, a transcranial magnetic stimulus was applied. The subject relaxed the target muscle after each magnetic stimulation. Five recordings were made for each contraction level, with a break between each maneuver.

Dynamic motor task

For the dynamic motor task the subjects executed a continuously increasing isometric (non-isotonic) contraction. The subject and the examiner had visual control of the actual contraction level (torque) by using an oscilloscope in front of the subject. Subjects were instructed to perform a smooth ramp contraction and the slope of the torque increment was recorded. This procedure allowed for the performance of comparable increments of force with a mean of 2.88 ± 1.2 Nm/s. A computer automatically triggered the transcranial magnetic stimulus when the required force level was achieved. The recordings and the trials corresponded to those of the static motor task.

Assessment of force generation

During the experiments, control subjects and patients lay in a supine position on an examination table. The torque of the upper ankle joint was assessed by a custom-built device, with the foot fixed in a slightly extended position (ankle joint angle of 105°). The device was fixed to the frame of the examination table. A ball joint with 3 degrees of freedom allowed a comfortable adjustment of the subject's foot, but prevented any movement at the ankle joint and any influence of the weigth of the lower limb on the torque measurement. A cushion was positioned under the subject's lower leg (calf), thus the foot was hanging freely and the weight of the lower limb could not influence the torque measurement. The position of the lower leg and of the foot were not changed during the whole experiment. To prevent any contraction of proximal muscles, such as the hip-flexors, the lower leg was firmly attached to the underlying cushion and movements of the hip and the whole body were restricted. Thus the subject was able to perform an isolated isometric foot dorsiflexion movement in the two motor-tasks.

Transcranial magnetic stimulation

A single pulse transcranial magnetic stimulation (TMS) was performed using a MagPro-Magnetic-Stimulator (DANTEC Medical A/S, Skovlunde, Denmark). For all measurements, a circular coil (diameter of 120 mm) was used. The coil position for stimulation of the TA was circa 4 cm rostral of Cz (Vertex). The duration of the biphasic transcranial single-pulse stimuli amounted to 200 μs. The individual coil placement and stimulation threshold were identified for each subject at the beginning of the measurements. The optimal position and TMS threshold for evoking TA MEP was determined during a static muscle contraction at 10 % of MVC. The stimulation strength was kept constant during the whole experiment.

EMG recordings and analysis

For the EMG recordings, silver/silver-chloride-surface electrodes with an inter-electrode distance of 2 cm, which were attached in the middle of TA and soleus muscle (SO), were used. All measurement data were saved on a hard disk for offline analysis. The data were analyzed by using Soleasy software (Alea Solutions, Zürich, Switzerland). The raw EMG-signals of the TA and SO muscles were rectified, amplified and filtered. The analyzed EMG was offset to zero. The sample frequency of the measurement was 2000 Hz and the EMG-amplification was set at 2000. The EMG signals were filtered with bandpass at 30 Hz to 1 kHz and recorded with a time window of 500 ms. The level of *background EMG* was evaluated by the calculation of the root mean square-values (RMS) of the TA muscle over a time window of 200 ms preceding the TMS-trigger [38].

MEP analysis

Several parameters were calculated to quantify the MEP responses. The MEP response was determined by calculating the RMS values over a time window of 20 ms from the onset of the rectified MEP [17]. MEP responses of the TA were accepted for further analysis when the MEP amplitude was at least 50 μV above background EMG and were followed by a silent period. By the subtraction of the background EMG from the total MEP the net MEP size was calculated. The MEP latency was determined from the TMS trigger to the onset of the MEP response.

Statistical procedures

The statistical analysis of the subjects' data was performed using SAS Systems software (SAS Institute Inc., Cary, NC, USA). Repeated measures analysis of variance with two levels of the between-conditions factor (static versus dynamic) and four levels of the within-conditions factor (contraction levels of 10 %, 20 %, 40 % and 60 % of MVC) and their interaction were used. The co-variance structure of the model was chosen using Akaike's Information Criterion and Schwarz's Bayesian Criterion.

Pair-wise comparisons were made between congruent contraction levels of the two conditions and between the contraction levels within the same condition. Since four comparisons were performed, α was set at $0.05/4 = 0.0125$.

To determine whether the difference in the net MEP between the static and dynamic conditions were different from zero for each contraction level, repeated measures ANOVA were performed. There was only one factor (level of contraction) with four levels (10 %, 20 %, 40 % and 60 %) with correction for multiple comparisons using Bonferroni's correction (α was set at 0.05).

The patients' data were analyzed using the analysis of variance, with again two levels of the between-condition factors (dynamic versus static) and the Bonferroni's correction. α was set at 0.05.

Results

Control subjects

Background EMG level

Repeated measures ANOVA found significant differences of the background EMG level between the static and dynamic conditions (10 % and 20 % levels $P = 0.0002$; 40 % and 60 % levels $P < 0.0001$). The background EMG during the dynamic contraction was 25 % to 38 % larger than during static contraction throughout all contraction levels. No significant differences were found when comparing the increment of background EMG activity at the different levels of contraction ($F[3,21] = 0.91$; $P = 0.45$).

Facilitation of MEP response

The net MEP responses were significantly different between the two conditions ($F[1,8] = 9.15$; $P = 0.0164$) and between the contraction levels ($F[3,24] = 17.23$; $P < 0.0001$). The interaction was just not significant ($F[3,23] = 2.96$; $P = 0.0535$).

Within the static condition, the net MEP responses did not differ between the 10 % and 20 % ($P = 0.54$) and 40 % and 60 % ($P = 0.96$) contraction levels. Some trend towards significant difference was found between the 10 % and 40 % ($P = 0.02$) and the 10 % and 60 % ($P = 0.02$).

Within the dynamic condition, a clear difference was found between the 10 % and 40 % ($P = 0.0068$), the 10 % and 60 % ($P < 0.0001$), the 20 % and 40 % ($P = 0.0039$) and the 20 % and 60 % ($P < 0.0001$) contraction levels.

The comparison of the net MEP was significantly different between the dynamic and static tasks (repeated measures ANOVA; $F[3,22] = 4.09$; $P = 0.0189$) (Fig. 1). During the dynamic task net MEPs were significantly increased at the 10 % ($P = 0.0003$) and 20 % contraction levels ($P = 0.0116$). At 40 % and 60 % no differences were observed ($P = 0.33$ and 0.82, respectively).

In order to exclude the possibility that the observed extra-facilitation during the dynamic task was due to a greater background EMG level, net MEP of matched background EMG levels were compared between the dynamic and static motor task at 10 % and 20 % MVC. At comparable levels of background EMG ($P = 0.25$) the net MEPs were significantly larger during the dynamic motor task ($P = 0.007$) (Fig. 2).

All the control subjects showed increased MEP responses during the dynamic motor task.
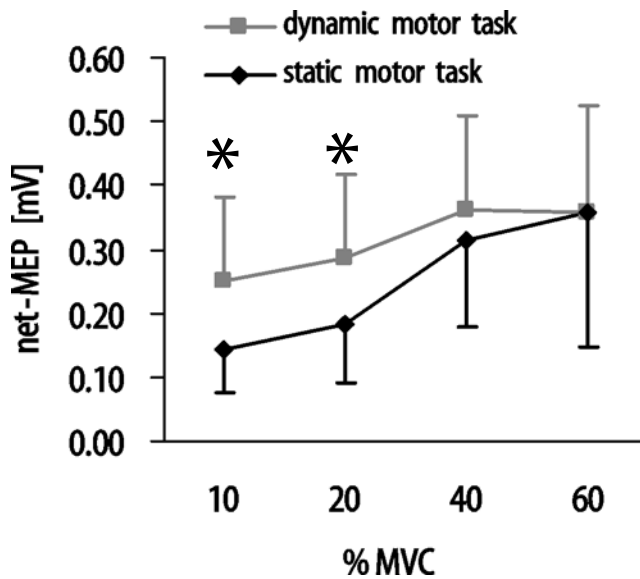
Fig. 1 Comparison of the mean net MEP values between the isometric dynamic and static motor task (* indicates a significant difference between the static and dynamic task, P < 0.01)
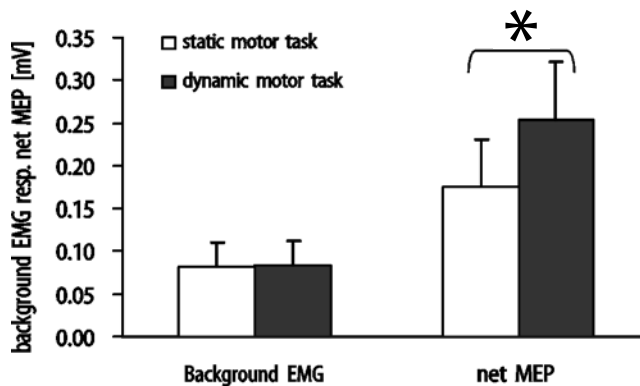

Fig. 2 Comparison of net MEP responses during the static and dynamic motor task at matched background EMG levels (* indicates a significant difference between the static and dynamic task, P < 0.01)

Patients with spinal cord injury

The net MEP responses of the iSCI patients showed a significant reduction in both the dynamic and static motor task (P < 0.001).

Corresponding to the excitability and size of net MEP, three subgroups could be distinguished (Fig. 3): group 1) 13/21 (61.9 %) of the patients showed a significant increase of the net MEP response during the dynamic motor task (P = 0.003), which corresponds to that seen in the control subjects, group 2) 5/21 (23.8 %) of the patients showed no difference between the net MEP size in the static and dynamic motor tasks, i. e. no facilitation during the dynamic motor task; and group 3) 3/21
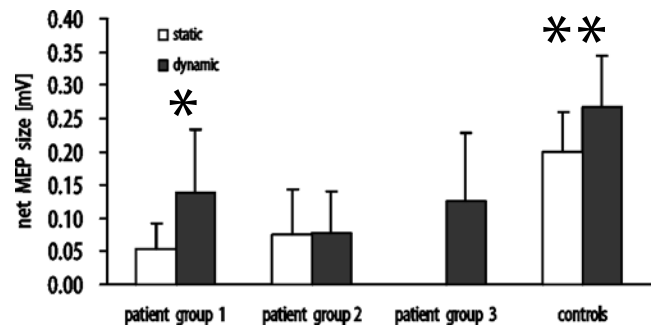

Fig. 3 Net MEP size in healthy subjects (controls) and iSCI patients during static and dynamic muscle contraction. In the iSCI patients, three subgroups of net MEP impairment could be distinguished (* indicates a significantly larger net MEP in the dynamic compared with the static motor task, P < 0.001). In the control subjects, the net MEP size of both motor tasks was significantly (** P < 0.007) larger compared to the iSCI patients

(14.2 %) of the patients showed a net MEP response only in the dynamic but not in the static motor task.

MEP latency

In the control subjects the MEP latency was not changed either by the task nor the level of MVC. The MEP latency during the dynamic motor task ranged from 23ms to 31ms (mean 27 ± 3ms) and during the static motor task from 25ms to 31ms (mean 27 ± 2.7ms). The iSCI patients showed significantly delayed MEP latencies (dynamic task: mean 34.9 ± 10 ms; static task: mean 35.4 ± 7 ms) but no significant differences between dynamic and static motor task (Fig. 4). The delay of the latency was not related to the reduction of MEP facilitation during the dynamic motor task.
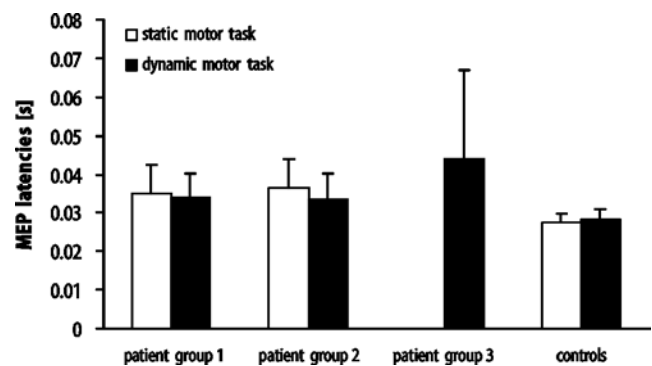

Fig. 4 MEP latencies of healthy controls and iSCI patients during dynamic and static motor task at 20 % MVC. In healthy subjects the MEP latencies were significantly shorter than in the patients while there was no difference in MEP latencies between the two motor tasks

Discussion

The assessment of task-dependent modulation of TA MEP can provide additional information about the impairment of spinal motor pathways in incomplete spinal lesions. In patients with iSCI the MEP amplitudes were significantly reduced and different patterns of impaired MEP facilitation could be distinguished. The potential relevance of these findings for the diagnostic assessment and follow-up examinations in patients with a spinal lesion will be discussed.

■ Task-dependent facilitation

The calculation of the *background EMG* in the control subjects during dynamic and static muscle contractions was applied to estimate the extent of spinal motoneuron pool recruitment [7, 29]. Since the background EMG was recorded at similar levels of torque generation for both tasks, the enhanced background EMG during the dynamic motor task indicates an increased MN-recruitment. This increase was significant at all contraction levels. This result is in accordance with studies on static and dynamic motor tasks of upper limb muscles [1, 34]. The difference in the discharge pattern can be attributed to a task-dependent recruitment of the MN pool. This was confirmed by studying the amplitude of descending spinal volleys to transcranial electrical and magnetic stimulation [10, 12, 15, 21, 41].

In the present study, at lower dynamic contraction levels a significant task-dependent facilitation comparable to upper limb muscles could be shown [25]. The net MEP size was calculated for all MEPs to assess changes of the MEP size independent of the level of background EMG [23, 26, 40]. The enhanced MEP size at lower levels of dynamic compared with static muscle contraction could be confirmed by matching the background EMG of both motor tasks.

■ Cortico-spinal pathways

The important contribution of cortico-spinal input to the MEP facilitation has been shown by TMS studies [31]. During the performance of skilled hand movements (precision grip) and the activation of lower limb muscles during walking, modulatory effects of descending inputs could be demonstrated [3, 5, 11, 18, 43]. During walking the TA activation in the swing phase is under a stronger cortico-motoneuronal (CM) control [40]. However, during motor tasks requiring a similar level of attention of the ankle flexors and extensors the CM connections seem to be equally linked and comparably influenced by segmental afferents [2, 6].

In the present study the analysis of MEPs during static and dynamic motor tasks allowed for the distinction of different patterns of impaired facilitation in iSCI patients. This observation adds to that of delayed MEP latencies described for iSCI patients [9]. In all iSCI patients studied here, the size of the MEP responses was significantly reduced in both motor tasks. About 2/3 of the patients showed a preserved facilitation with an enhanced MEP response in the dynamic motor task. In the remaining 1/3 of iSCI patients MEP facilitation was impaired. Either there was no extra-facilitation of MEP in the dynamic compared with the static motor task or a MEP response could only be elicited in the dynamic motor task. These findings indicate different forms of impaired MEP facilitation that were not related to the delay of the MEP latency. Such differences became only evident when the task-dependent effect on MEP size was analyzed. In contrast to the MEP triple stimulation technique (TST) the present study focused on facilitatory MEP effects [28]. However, the TST has the advantage of resynchronizing discharges due to central motor conduction failures that allows for the quantification of the conducting central motor tracts [4, 20].

Besides diagnostic purposes, neurophysiological recordings are repeatedly applied in acute iSCI patients during the clinical course to monitor the recovery of spinal motor pathways. In traumatic iSCI MEP latencies remain unchanged even in patients with a relevant improvement of sensorimotor function [9]. The task-dependent MEP facilitation could provide additional information about the function of spinal motor pathways [10]. The question how far the changes of MEP facilitation can be related to clinical symptoms in iSCI needs further evaluation.

In conclusion, the present observations are of potential clinical significance for three reasons. First, the performance of controlled levels of muscle contraction allows for a comparison of the MEP size between control subjects and patients. Second, in patients where it is difficult to record MEP responses of the lower limb muscles during a static motor task, an additional facilitation can be achieved by dynamic muscle activation. Third, assessing changes in facilitation provides additional information complementary to the delay of MEP responses. Therefore, the task-dependent modulation of lower limb MEP represents an additional approach for diagnosis and follow-up of impaired spinal motor pathways.

References

1. Aranyi Z, Mathis J, Hess CW, Rosler KM (1998) Task-dependent facilitation of motor evoked potentials during dynamic and steady muscle contractions. Muscle Nerve 21(10):1309–1316

2. Bawa P, Chalmers GR, Stewart H, Eisen AA (2002) Responses of ankle extensor and flexor motoneurones to transcranial magnetic stimulation. J Neurophysiol 88(1):124–132

3. Brouwer B, Ashby P, Midroni G (1989) Excitability of corticospinal neurons during tonic muscle contractions in man. Exp Brain Res 74(3):649–652

4. Buhler R, Magistris MR, Treffert A, Hess CW, Rosler KM (2001) The triple stimulation technique to study central motor conduction to the lower limbs. Clin Neurophysiol 112(5):938–949

5. Capaday C, Lavoie BA, Barbeau H, Schneider C, Bonnard M (1999) Studies on the corticospinal control of human walking: I. Responses to focal transcranial magnetic stimulation of the motor cortex. J Neurophysiol 81(1):129–139

6. Christensen LO, Andersen JB, Sinkjaer T, Nielsen J (2001) Transcranial magnetic stimulation and stretch reflexes in the tibialis anterior muscle during human walking. J Physiol 531(2):545–557

7. Clamann HP (1993) Motor unit recruitment and the gradation of muscle force. Phys Ther 73(12):830–843

8. Claus D, Weis M, Spitzer A (1991) Motor potentials evoked in tibialis anterior by single and paired cervical stimuli in man. Neurosci Lett 125(2):198–200

9. Curt A, Keck ME, Dietz V (1998) Functional outcome following spinal cord injury: Significance of motor-evoked potentials. Arch Phys Med Rehab 79:81–86

10. de Noordhout AM, Pepin JL, Gerard P, Delwaide PJ (1992) Facilitation of responses to motor cortex stimulation: effects of isometric voluntary contraction. Ann Neurol 32(3):365–370

11. de Noordhout AM, Rapisarda G, Bogacz D, Gerard P, De Pasqua V, Pennisi G, Delawaide PJ (1999) Corticomotoneuronal synaptic connections in normal man: an electrophysiological study. Brain 122:1327–1340

12. Di Lazzaro V, Oliviero A, Proficue P, Insola A, Mazzone P, Tonali P, Rothwell JC (1999) Effects of voluntary contraction on descending volleys evoked by transcranial electrical stimulation over the motor cortex hand area in conscious humans. Exp Brain Res 124:525–528

13. Di Lazzaro V, Oliviero A, Profice P, Ferrara L, Saturno E, Pilato F, Tonali P (1999) The diagnostic value of motor evoked potentials. Clin Neurophysiol 110(7):1297–1307

14. Ellaway PH, Davey NJ, Maskill DW, Rawlinson SR, Lewis HS, Anissimova NP (1998) Variability in the amplitude of skeletal muscle responses to magnetic stimulation of the motor cortex in man. Electroencephalogr Clin Neurophysiol 109(2):104–113

15. Enoka RM (1995) Morphological features and activation patterns of motor units. J Clin Neurophysiol 12(6):538–559

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

17. Funase K, Miles TS, Gooden BR (1999) Trial-to-trial fluctuations in H-reflexes and motor evoked potentials in human wrist flexors. Neurosci Lett 271(1):25–28

18. Hasegawa Y, Kasai T, Tsuji T, Yahagi S (2001) Further insight into the task-dependent excitability of motor evoked potentials in first dorsal interosseus muscle in humans. Exp Brain Res 140(4):387–396

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

20. Humm AM, Z'Graggen WJ, von Hornstein NE, Magistris MR, Rosler KM (2004) Assessment of central motor conduction to intrinsic hand muscles using the triple stimulation technique: normal values and repeatability. Clin Neurophysiol 115(11):2558–2566

21. Jones KE, Lyons M, Bawa P, Lemon RN (1994) Recruitment order of motoneurons during functional tasks. Exp Brain Res 100(3):503–508

22. Kasai T, Kawai S, Kawanishi M, Yohagi S (1997) Evidence for facilitation of motor evoked potentials (MEPs) induced by motor imagery. Brain Res 744(1):147–150

23. Keck ME, Pijnappels M, Schubert M, Colombo G, Curt A, Dietz V (1998) Stumbling reactions in man: influence of corticospinal input. Electroencephalogr Clin Neurophysiol 109(3):215–223

24. Kiers L, Cros D, Chiappa KH, Fang J (1993) Variability of motor potentials evoked by transcranial magnetic stimulation. Electroencephalogr Clin Neurophysiol 89(6):415–423

25. Kimura T, Yamanaka K, Nozaki D, Nakazawa K, Miyoshi T, Akai M, Ohtsuki T (2003) Hysteresis in corticospinal excitability during gradual muscle contraction and relaxation in humans. Exp Brain Res 152:123–132

26. Kischka U, Fajfr R, Fellenberg T, Hess CW (1993) Facilitation of motor evoked potentials from magnetic brain stimulation in man: a comparative study of different target muscles. J Clin Neurophysiol 10(4):505–512

27. Lentz M, Nielsen JF (2002) Post-exercise-facilitation and depression of M wave and motor evoked potentials in healthy subjects. Clin Neurophysiol 113(7):1092–1098

28. Magistris MR, Rosler KM, Truffert A, Landis T, Hess CW (1999) A clinical study of motor evoqued potentials using a triple stimulation technique. Brain 122 (2):265–279

29. Maton B (1980) Fast and slow motor units: their recruitment for tonic and phasic contraction in normal man. Eur J Appl Physiol Occup Physiol 43(1):45–55

30. Maynard FM Jr, Bracken MB, Crearey G, Ditunno JF Jr, Donovan WH, Ducke TB (1997) International standards for neurological and functional classification of spinal cord injury. American Spinal Injury Association. Spinal Cord 35:266–274

31. Mills KR, Kimiskidis V (1996) Cortical and spinal mechanisms of facilitation to brain stimulation. Muscle Nerve 19(8):953–958

32. Nielsen J, Petersen N (1995) Evidence favouring different descending pathways to soleus motoneurones activated by magnetic brain stimulation in man. J Physiol 486(3):779–788

33. Palmer E, Ashby P (1992) Corticospinal projections to upper limb motoneurones in humans. J Physiol 448:397–412

34. Romaiguere P, Vedel JP, Pagni S (1989) Fluctuations in motor unit recruitment threshold during slow isometric contractions of wrist extensor muscles in man. Neurosci Lett 103(1):50–55

35. Rossi F, Triggs WJ, Eisenschenk S (1999) Topographic differences in task-dependent facilitation of magnetic motor evoked potentials. Neurology 52(3):537–540

36. Rossini PM, Rossi S (1998) Clinical applications of motor evoked potentials. Electroencephalogr Clin Neurophysiol 106(3):180–194

37. Rothwell JC, Thompson PD, Day BL, Dick JP, Kachi T, Cowan JM, Marsden CD (1987) Motor cortex stimulation in intact man. 1. General characteristics of EMG responses in different muscles. Brain 110(5):1173–1190

38. Sbriccoli P, Bazzucchi I, Rosponi A, Bernardi M, De Vito G, Felici F (2003) Amplitude and spectral characteristics of biceps Brachii s EMG depend upon speed of isometric force generation. J Electromyogr Kinesiol 13(2):139–147

39. Schieppati M, Trompetto C, Abbruzzese G (1996) Selective facilitation of responses to cortical stimulation of proximal and distal arm muscles by precision tasks in man. J Physiol 49(12):551–562

40. Schubert M, Curt A, Jensen L, Dietz V (1997) Corticospinal input in human gait: Modulation of magnetically evoked motor responses. Exp Brain Res 115(2):234–246

41. Sogaard K (1995) Motor unit recruitment pattern during low-level static and dynamic contractions. Muscle Nerve 18(3):292–300

42. Thompson PD, Day BL, Rothwell JC, Dressler D, Maertens de Noordhout A, Marsden CD (1991) Further observations on the facilitation of muscle responses to cortical stimulation by voluntary contraction. Electroencephalogr Clin Neurophysiol 81(5):397–402

43. Turton A, Lemon RN (1999) The contribution of fast corticospinal input to the voluntary activation in normal subjects and in stroke patients. Exp Brain Res 129(4):559–572

44. Ugawa Y, Terao Y, Hanajima R, Sakai K, Kanazawa I (1995) Facilitatory effect of tonic voluntary contraction on responses to motor cortex stimulation. Electroencephalogr Clin Neurophysiol 97(6):451–454