Exp Brain Res (2003) 148:261–265
DOI 10.1007/s00221-002-1299-y

RESEARCH ARTICLE

Toshiaki Furubayashi · Kenichi Sugawara · Tatsuya Kasai · Akito Hayashi · Ritsuko Hanajima · Yasushi Shiio · Nobue Kobayashi Iwata · Yoshikazu Ugawa

Remote effects of self-paced teeth clenching on the excitability of hand motor area

Received: 3 April 2002 / Accepted: 23 September 2002 / Published online: 12 November 2002

Abstract We studied remote effects of teeth clenching on motor cortical and spinal cord excitability using transcranial magnetic stimulation (TMS), brainstem electrical stimulation (BES), and ulnar nerve stimulation (F-wave) in eight normal volunteers. The TMS, BES, and ulnar nerve stimulation at the wrist were given at different intervals (0–200 ms) after the onset of masseter contraction. Surface electromyographic responses were recorded from the first dorsal interosseous muscle. Responses at different intervals were compared with the response elicited when the subject made no teeth clenching (control response). In TMS, conditioned responses (during teeth clenching) were significantly larger than the control at all intervals. In contrast, in BES and F-waves, conditioned responses were not larger than the control at an early phase (intervals shorter than 50 ms), whereas they were larger than the control at later intervals (longer than 50 ms). These results suggest that facilitation occurs in the hand motor area at the early phase of teeth clenching, and spinal facilitation dominates at its late phase. This time course of facilitation may indicate that the motor cortex must regulate hand muscles finely at the early phase of teeth clenching, and spinal cord may stabilize them firmly at the late phase. The excitability changes of the hand motor area may be in parallel with that of the masseter motor area which reflects the pattern of masseter contraction when the subject activates the masseter muscle phasically at the early phase and sustains that contraction at the late phase.

Keywords Teeth clenching · Remote facilitation · Magnetic stimulation · Motor cortex · Brainstem stimulation

Introduction

We sometimes clench our teeth when we try to do something with great effort, such as lifting a heavy thing, hitting a ball, kicking a ball, and so on. This maneuver is also used to reinforce the H-reflex in the lower limb muscles in clinical practice, similar to the Jendrassik maneuver. In the former, teeth clenching is not an intended movement but one aspect of general motor system activation in powerful tasks. In contrast, however, the teeth clenching itself is an intended movement in the latter. A few investigators (Miyahira et al. 1996; Takada et al. 2000; Zehr and Stein 1999) have studied mechanisms underlying this technique of intentional teeth clenching using H-reflexes of the lower limb muscles. One report has studied excitability changes of the motor systems for leg and hand muscles induced by teeth clenching using transcranial magnetic simulation (TMS) and brainstem electrical stimulation (BES) (Boroojerdi et al. 2000).

In the present communication, we studied cortical and spinal cord excitability changes in the motor pathways for a hand muscle at several timings during the intentional teeth clenching. We show that enhancement occurs only at the hand motor area at the early phase of teeth clenching.

T. Furubayashi · R. Hanajima · Y. Shiio · N.K. Iwata
Y. Ugawa (✉)
Department of Neurology, Division of Neuroscience,
Graduate School of Medicine, University of Tokyo, 7-3-1, Hongo,
Bunkyo-ku, Tokyo 113-8655, Japan
e-mail: ugawa-tky@umin.ac.jp
Tel.: +81-3-58008672
Fax: +81-3-58006548

K. Sugawara
Department of Restorative Science, Faculty of Medical Professions,
Kawasaki University of Medical Welfare, Japan

T. Kasai
Division of Sports and Health Sciences,
Graduate School for International Development and Cooperation,
Hiroshima University, Japan

A. Hayashi
Department of Neurology, Institute of Clinical Medicine,
University of Tsukuba, Japan

Materials and methods

Subjects

Subjects were eight normal volunteers, aged 29–46 years. All of them had given their written informed consent prior to the experiments. The procedures described here were approved by the Ethics Committee of the University of Tokyo.

Methods

Subjects comfortably sat on a reclining chair with their arms supported. Surface electromyographic (EMG) activities were recorded from the right first dorsal interosseous muscle (FDI) with pairs of surface cup electrodes in a belly-tendon montage. The EMGs were also recorded from the right masseter muscles. The active electrode was on the muscle belly, and the reference electrode on the mandible next to the masseter. Signals were amplified with filters set at 100 Hz and 3 KHz and recorded by a computer (Signal Processor DP-1200; GE Marquette Medical Systems) for the later off-line analysis. The onset of masseter EMGs was used to trigger TMS, BES, and ulnar nerve electrical stimulation for F-waves. All subjects were trained to perform teeth clenching without any activity in the FDI. Responses elicited by TMS or BES, or F-waves were recorded from relaxed FDI. These responses were measured to evaluate the motor cortical and spinal cord excitability.

The TMS was performed with a Magstim 200 magnetic stimulator with a round coil centered over the vertex. The coil current flowed in an anticlockwise direction as viewed from above to preferentially activate the left hemisphere. The intensity was adjusted to elicit a response of 0.1–0.2 mV in the relaxed FDI in each subject.

The BES was performed with a high voltage electrical stimulator (Digitimer D180A stimulator). Cup electrodes were fixed at the posterior edges of the bilateral mastoid processes. The anode was on the left side and the cathode on the right. The stimulus intensity was carefully adjusted to elicit a control response with a similar amplitude as a magnetic control response in each subject.

To study spinal cord excitability changes during teeth clenching, we also recorded F-waves from the right FDI. In five subjects, F-waves were elicited with an electrical stimulus (rectangular constant current, 1 ms duration) at the wrist. The stimulus intensity was fixed to evoke F-waves of around 0.2 mV.

In each subject, we first determined the intensity of stimulation to evoke a control response of about 0.1–0.2 mV in the relaxed FDI for TMS, BES, and F-waves. These intensities were 40% to 57% of the maximum stimulator output in TMS, 20% to 44% in BES (1.1–1.3 times threshold), and 7–10 mA in F-waves. We selected control responses of this size because such small responses are susceptible to any kind of modulatory effect, whether they are facilitatory or inhibitory (Ohki et al. 1994; Terao et al. 1995; Ugawa et al. 1995). If the control response is a large one elicited by a strong stimulus (such as >5.0 mV), it is usually resistant to modulatory effects. We fixed the intensities throughout the experiments. Ten control responses were obtained for TMS, BES, and F-waves. Thereafter, we performed a randomized conditioning experiment. Conditioning was teeth clenching and the test stimulus was TMS, BES, or ulnar nerve stimulation. Every subject practiced starting clenching the teeth abruptly and sustaining it for 300 ms or more, and all of them were able to clench sufficiently in the following experiments. Duration of actual EMG potentials from the masseter muscles was 300–500 ms, which indicates that masseter muscles were activated throughout the analysis time of this experiment (see below). In one session, several conditioned trials in which TMS or BES was given at different intervals (0, 40, 80, 120, and 160 ms) after the onset of masseter EMG were randomly intermixed. In five subjects, an electrical stimulus for F-waves was also intermixed. The onset of voluntary masseter contraction was detected by the computer when rectified EMG exceeded the preset level, and TMS, BES, or ulnar nerve stimulus was given at a certain interval after this onset. The actual onset of EMG activities always preceded this onset by the time during which rectified EMG increased to the preset level from the silence. The accurate interval between the onset of EMG of the masseter muscle and the stimulus (TMS/BES/F-waves) was measured in each trial on the off-line screen by the computer. In the analysis, we used these accurate intervals. Because of these techniques, the actual interval was longer than the interval from the onset defined by the computer to the stimulus by the time between the onset of EMG and the preset level of EMG. As shown in Fig. 2, therefore, the accurate intervals were longer by some 20 ms. Latency differences among responses to TMS, BES, and F-waves were 1.5–2.0 ms. Since these latency differences were much shorter than the time bin of our final analysis (50 ms), we used actual intervals for analysis (not compensated for the latency differences).

Each condition consisted of 10 trials. Intertrial intervals were randomly set at 10±2 s by the computer and a go signal (red light) was given to the subject. After the signal, the subject made voluntary clenching at any time when she/he was ready. They did not try to perform it as early as possible but performed it when they were ready. This performance, therefore, is not a reaction time task but a kind of self-paced teeth clenching. In each trial of the conditioning experiments, recordings were triggered by this self-paced voluntary clenching after the cue signal. One session included 20 trials of randomly arranged different conditions (stimulation and interval). Several sessions were performed in order to construct the entire time course of the effect. Ten control responses for TMS, BES, and F-waves were recorded before each session. In these kinds of experiments, ideally, control and conditioned trials should be randomly intermixed in the same session. In our experiments, however, such randomization could not be done because the masseter contraction triggered the stimulation in conditioned trials, and teeth clenching should not be done in control trials. Because the amplitudes of those control responses before different sessions were not significantly different in the same subject (one factor ANOVA, $P>0.05$), we used all control responses (40 or 50 responses) as one group of control condition in the analysis. In one subject, conditioned responses under the same condition from several sessions were also used as one group of responses.

We measured the size of responses from FDI and the accurate interval between the actual EMG onset of masseter muscle detected by inspection and TMS/BES/ulnar nerve stimuli for F-waves in all individual trials. To show the time course of effects of teeth clenching, the size ratio of a conditioned response to that of the average control response was plotted against the accurate intervals. Response sizes were depicted with these ratios (size ratio) in order to cancel interindividual variability of absolute EMG amplitudes. Similar time courses of effects were seen in all subjects. We performed statistical comparisons using the pooled data from all the subjects. The accurate intervals were grouped into four time bins ($0 < ISI \leq 50$, $50 < ISI \leq 100$, $100 < ISI \leq 150$, $150 < ISI \leq 200$). In TMS/BES/F-waves experiments, we compared sizes of responses from FDI between control and conditioned trials. A one factor (group: control and four interval groups) ANOVA test was used to assess a significant effect of interval group on the size of responses from FDI in each kind of response. *Post hoc* comparisons were performed using a *t*-test with the Bonferroni correction for multiple comparisons. The statistical significance level was set at $P<0.05$.

Results

Figure 1 shows typical responses in a single subject. Responses to TMS are on the left, those to BES on the middle, and F-waves on the right. Control responses were almost the same in size (about 0.2 mV). The lower rows show conditioned responses to stimuli given at 40 and 80 ms after the onset of masseter contraction automatically detected by the computer. At an interval of 40 ms,

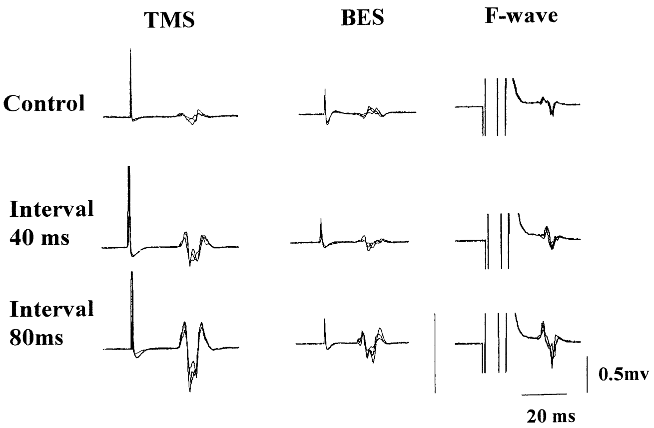

Fig. 1 Typical responses from the first dorsal interosseous (FDI) muscle in a single subject. Responses to transcranial magnetic stimulation (TMS), brainstem electrical stimulation (BES), and ulnar nerve stimulation (F-wave) are shown from *left to right*. Control responses are shown in the *top row*, and conditioned responses at 40 and 80 ms after the onset of teeth clenching defined by the computer are shown in the *following rows*. At the 40-ms interval the conditioned response was larger than the control response in TMS, whereas it was almost the same in size in BES and F-wave. At an 80-ms interval, in contrast, all three kinds of responses were larger than the control

the conditioned response to TMS was larger than the control response, whereas the response to BES or F-waves was not affected by the teeth clenching. At an interval of 80 ms, all responses were larger than the control responses.

Figure 2 shows sizes of responses elicited by TMS, BES, or ulnar nerve stimuli given at different intervals after the actual onset of masseter EMG in all trials in all the subjects. The mean (±SD) size of control responses to TMS was 0.16±0.06 mV, that for BES responses 0.14±0.04 mV, and 0.18±0.03 mV for F-waves. These did not significantly differ (ANOVA: F=3.108, P=0.214). Response sizes are shown as ratios of conditioned responses to the average control response. Dots indicate responses to TMS, circles those to BES, and triangles F-waves. The abscissa indicates intervals between the onset of masseter muscular contraction and stimuli, and the ordinate indicates response size ratios. At the early phase of teeth clenching (0–50 ms after the onset of masseter EMG), magnetic cortical responses were larger than the control response, whereas those elicited by BES or F-waves were as large as the control responses. However, at later intervals (>50 ms), all responses to TMS and those to BES and F-waves were similarly enlarged by teeth clenching.

Mean size ratios at four different groups of actual intervals after the onset of masseter EMG ($0 < ISI \leq 50$, $50 < ISI \leq 100$, $100 < ISI \leq 150$, $150 < ISI \leq 200$) were obtained from all single responses. They are shown in Fig. 3. In all responses to TMS, BES, and F-waves, the interval had a significant effect on the size ratio (ANOVA; TMS: F=3.252, P=0.033; BES: F=4.791, P=0.0098; F-wave: F=4.245, P=0.023). *Post hoc* analysis

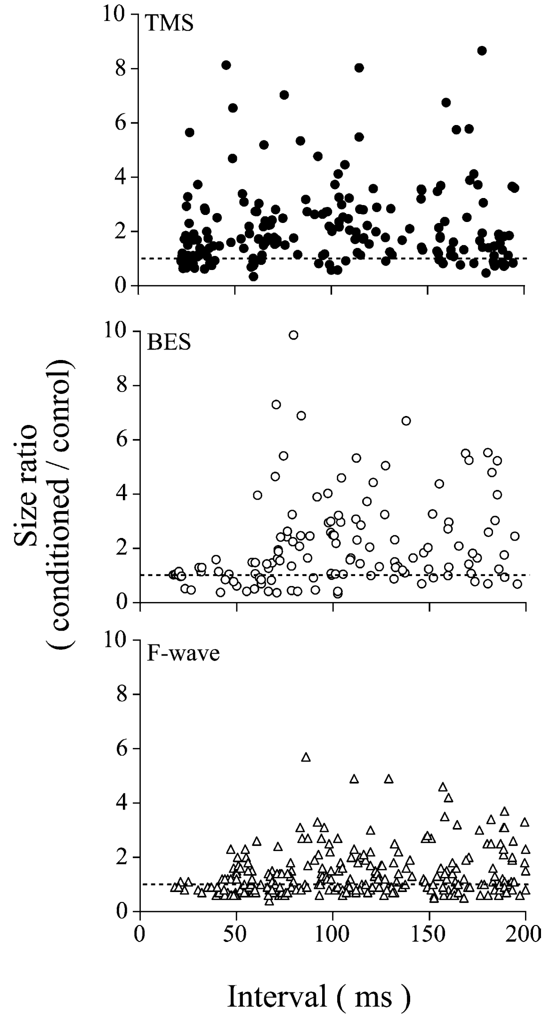

Fig. 2 Response sizes against the interval after the onset of masseter contraction. Responses to TMS are shown in the *top row*, those to BES in the *second row*, and F-waves in the *bottom row*. The size ratios of the conditioned response to the control are shown against the actual intervals between the onset of masseter EMG and the stimuli. The TMS responses were facilitated at all intervals of our analysis time. In contrast, in responses to BES or F-wave, facilitation occurred at the late phase (>50 ms) and no facilitation at the early phase (≤50 ms)

revealed that conditioned responses to TMS were significantly enhanced at all interval groups (0–200 ms), whereas those to BES and F-waves at three interval groups (50–200 ms). These indicated that, at the early phase of teeth clenching (0–50 ms intervals), magnetic cortical responses were enlarged without any significant size changes in responses to BES or F-waves.

Discussion

Our present results are summarized as follows. At the early phase of teeth clenching (shorter than 50 ms after its onset), magnetic cortical responses were facilitated with no facilitation of responses to BES or F-waves. At the

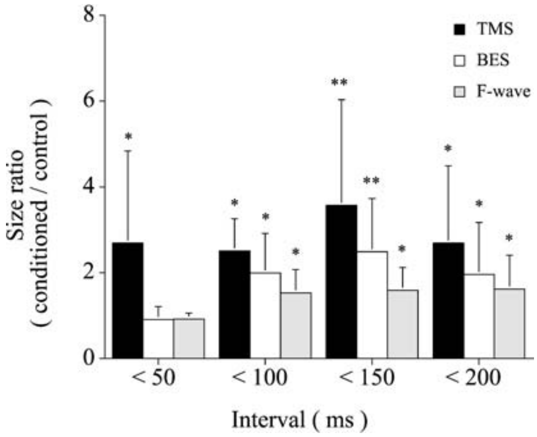

Fig. 3 Mean ± SD size ratios at four interval groups (0–50, 50–100, 100–150, 150–200 ms) are shown. *Filled columns* are for TMS, *open columns* for BES, and *shaded columns* for F-waves. ANOVA with one factor (control and four interval groups) revealed a significant effect of the interval group on the size ratio in all responses. *Post hoc* analysis showed the following significant differences. In response to TMS, the size ratios were significantly larger than the control at all interval groups. In response to BES and F-wave they were significantly larger than the control at the three later interval groups. *P<0.05, **P<0.01

later phases (longer than 50 ms), in contrast, all three kinds of response were facilitated.

The size of responses to TMS reflects the excitability of whole motor systems (cortex to muscle), and that of responses to BES reflects the excitability of motor systems caudal to the activation site in BES (foramen magnum level) (Ugawa et al. 1991, 1994). Because spinal motoneurone pools for TMS, BES, and F-waves are not completely the same, comparisons of these response sizes may not show the level of excitability changes. However, collision experiments between TMS and BES in humans (Ugawa et al. 1991, 1994) and in monkeys (Olivier et al. 2002) suggest that considerable overlap is present between the descending tracts activated by TMS and BES. This indicates that considerable numbers of spinal motoneurones are the same between TMS and BES. These problems have been reviewed (Ugawa 2002). At present, therefore, it is not unreasonable to speculate the level of excitability changes by comparing response sizes between TMS and BES. Moreover, our finding that the time course of modulation of F-wave sizes was similar to that of responses to BES also suggests that spinal motoneuronal excitability is reasonably speculated by time courses of F-waves or responses to BES because F-waves should reflect only spinal cord excitability. Our present findings, therefore, suggest that enhancement occurs at the hand motor area at the early phase without any enhancement of spinal cord excitability. At the later phases, however, enhancement occurs at the spinal motoneurones. The observation that larger enhancement occurred in TMS responses than in BES responses or F-waves at the three later interval groups may indicate that cortical facilitation is associated with spinal facilitation at these later phases. However, we cannot definitely evaluate whether cortical enhancement coexists with the spinal cord enhancement, because responses to TMS may be enlarged more than those to BES even when the excitability of spinal cord is increased without any enhancement of the motor cortex because of temporal summation of EPSPs by multiple descending volleys. Based on these observations, we conclude that the hand motor area is facilitated at the early phase of intentional teeth clenching, and at the later phase, spinal cord is facilitated possibly with cortical facilitation.

A few investigations have studied effects of teeth clenching on the motor systems using H-reflexes (Delwaide and Toulouse 1980, 1981; Kawamura and Watanabe 1975; Miyahira et al. 1996; Takada et al. 2000). They demonstrated that, in lower limb muscles, H-reflexes were facilitated by teeth clenching even just before the onset of masseter contraction and during the contraction. This indicates that the excitability of motoneurones is increased by teeth clenching at its early and late phases. The physiological function of this facilitation may be to improve stability of stance (Takada et al. 2000; Takahashi et al. 2001). This time course of the effect has a small difference from our results. We showed spinal facilitation occurs at intervals longer than 50 ms after the onset of masseter contraction.

We consider two major factors which should explain this difference. The first is that we studied a hand muscle, but the others studied the lower limb muscles. However, one study (Péréon et al. 1995) showed that, even in lower limb muscles, the Jendrassik maneuver evoked spinal facilitation in the same manner as our results. Therefore, our time course of spinal facilitation may not be inconsistent with previous reports. Boroojerdi et al. (2000) revealed that, during teeth clenching, facilitation occurs at the cortical and subcortical sites within the hand motor system, and only at the subcortical site in the motor system for lower limb muscles. This is also consistent with our finding that facilitation occurs at both the cortex and spinal cord in the motor system for FDI. Why does only cortical facilitation occurs at the early phase in FDI? In tasks with great effort, we need non-specific spinal facilitation in the lower limb muscles for stabilizing the stance firmly even at the early phase (Toulouse and Delwaide 1980). Spinal facilitation at the early phase observed in the lower limb muscles reflects this function. However, hand muscles are not only used for powerful grip. We need fine, sophisticated regulation of the motor outputs to hand muscles, especially at the onset (early phase) of our movements. Our finding of the cortical facilitation at the early phase of intentional teeth clenching indicates that hand muscles should be freely controlled by the motor cortex without any restriction of the spinal cord. This must support fine, programmed movements of hand muscles at the early phase of intentional teeth clenching. In contrast, at the late phase, hand muscles should be stabilized firmly to maintain the powerful movement because the fine movement is already ordered.

The second possible explanation is the differences in performance between the phases of teeth clenching. The subject often clenches the teeth phasically, sometimes continuously clenches, or starts clenching rapidly and continues to clench for a while. We selected the last pattern of teeth clenching. We trained the subjects to start teeth clenching abruptly (phasic movement) and maintain it (tonic movement) for a while. In such teeth clenching, phasic rapid movement occurs at the early phase and tonic movement at the late phase. It is well known that cortical facilitation occurs in the hand motor area in complex tasks more than simple tasks (Flament et al. 1993), or in voluntary contraction more than in power grip (Datta et al. 1989). In the tonic contraction of hand muscles, other fiber systems than the corticospinal tract must contribute much to the maintenance of EMG activities (Brouwer et al. 1989). These observations suggest that less corticospinal tract facilitation should be seen in tonic contraction than phasic contraction. In analogy to the hand motor area, the motor cortex for the masseter muscle must be much facilitated at the early phase of our teeth clenching than the late phase. The hand motor area may change its excitability in parallel with the masseter motor cortex, which leads to cortical facilitation of the hand motor area at the early phase of teeth clenching. In the present experiments, the subjects performed a self-paced clenching after the cue presented by the computer. This may explain that cortical facilitation did occur at the beginning of teeth clenching. In the hand motor area, cortical facilitation occurred in self-paced movements earlier than in reaction time tasks (Chen et al. 1998). This facilitation was seen even before EMG activities. If we apply the analogy of this phenomenon of finger movements to teeth clenching, cortical facilitation must be elicited at the early phase of a self-paced teeth clenching.

In conclusion, we have shown that the hand motor area is facilitated without any spinal cord facilitation at the early phase of intentional teeth clenching, and spinal facilitation dominates at its late phase. This time course of facilitation may be good for fine, purposeful, movements of hand muscles, or may reflect that phasic teeth clenching was followed by a tonic clenching in our experiments.

Acknowledgements A part of this work was supported by Research Projects Grant-in-Aid for Scientific Research numbers 12680768 (Y.U.) and 10680031 (T.K.) from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

References

Boroojerdi B, Battaglia F, Muellbacher W, Cohen LG (2000) Voluntary teeth clenching facilitates human motor system excitability. Clin Neurophysiol 111:988–993

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

Chen R, Yaseen Z, Cohen LG, Hallett M (1998) Time course of corticospinal excitability in reaction time and self-paced movements. Ann Neurol 44:317–325

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 418:13–23

Delwaide PJ, Toulouse P (1980) Jendrassik maneuver vs controlled contractions conditioning the excitability of soleus monosynaptic reflexes. Arch Phys Med Rehabil 61:505–510

Delwaide PJ, Toulouse P (1981) Facilitation of monosynaptic reflexes by voluntary contraction of muscles in remote parts of the body. Brain 104:701–719

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

Kawamura T, Watanabe S (1975) Timing as a prominent factor of the Jendrassik manoeuvre on the H reflex. J Neurol Neurosurg Psychiatry 38:508–516

Miyahara T, Hagiya N, Ohyama T, Nakamura Y (1996) Modulation of human soleus H reflex in association with voluntary clenching of the teeth. J Neurophysiol 76:2033–2041

Ohki Y, Suzuki T, Ugawa Y, Uesaka Y, Sakai K, Kanazawa I (1994) Excitatory of the motor cortex associated with the E2 phase of cutaneous reflexes in man. Brain Res 633:343–347

Olivier E, Baker SN, Lemon RN (2002) Comparison of direct and indirect measurements of the central motor conduction time in the monkey. Clin Neurophysiol 113:469–477

Péréon Y, Genet R, Guihéneuc P (1995) Facilitation of motor evoked potentials: timing of Jendrassik maneuver effects. Muscle Nerve 18:1427–1432

Takada Y, Miyahara T, Tanaka T, Ohyama T, Nakamura Y (2000) Modulation of H reflex of pretibial muscles and reciprocal Ia inhibition of soleus muscle during voluntary teeth clenching in humans. J Neurophysiol 83:2063–2070

Takahashi T, Ueno T, Taniguchi H, Ohyama T, Nakamura Y (2001) Modulation of H reflex of pretibial and soleus muscles during mastication in humans. Muscle Nerve 24:1142–1148

Terao Y, Ugawa Y, Uesaka Y, Hanajima R, Genba SK, Ohki Y, Kanazawa I (1995) Input-output organization in the hand motor area of human motor cortex. Electroencephalogr Clin Neurophysiol 97:375–381

Toulouse P, Delwaide PJ (1980) Reflex facilitation by remote contraction: topographic aspects. Arch Phys Med Rehabil 61:511–516

Ugawa Y (2002) Stimulation at the foremen magnum level as a tool to separate cortical from spinal cord excitability changes. Adv Clin Neurophysiol (Suppl Clin Neurophysiol) 54:216–222

Ugawa Y, Rothwell JC, Day BL, Thompson PD, Marsden CD (1991) Percutaneous electrical stimulation of corticospinal pathways at the level of the pyramidal decussation in humans. Ann Neurol 29:418–427

Ugawa Y, Uesaka Y, Terao Y, Hanajima R, Kanazawa I (1994) Magnetic stimulation of corticospinal pathways at the foramen magnum level in humans. Ann Neurol 36:618–624

Ugawa Y, Uesaka Y, Terao Y, Hanajima R, Kanazawa I (1995) Magnetic stimulation over the cerebellum in humans. Ann Neurol 37:703–713

Zehr EP, Stein RB (1999) Interaction of the Jendrassik maneuver with segmental presynaptic inhibition. Exp Brain Res 124:474–480