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Article *in* Experimental Brain Research · March 2002

Impact Factor: 2.04 · DOI: 10.1007/s00221-001-0978-4 · Source: PubMed

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Exp Brain Res (2002) 143:149–159
DOI 10.1007/s00221-001-0978-4

RESEARCH ARTICLE

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Effects of changes in hip joint angle on H-reflex excitability in humans

Received: 15 June 2001 / Accepted: 8 November 2001 / Published online: 16 January 2002

Abstract We examined the amplitude modulation of the soleus (Sol) H-reflex during controlled variations of the hip joint angle in 21 healthy adult human subjects. Hip angle variations were imposed separately, or in combination either with stimulation of the plantar skin or with electrical activation of muscle afferents from the medial gastrocnemius (MG) nerve. We found that with subjects in the supine position, flexion of the hip significantly depressed Sol H-reflex excitability, by as much as 50% of control reflex values (Ho) recorded at 10° of hip flexion. Conversely, significant facilitation of the H-reflex was observed when the hip joint was extended (10°), with amplitudes reaching 200±15.3% of Ho. Changes in H-reflex amplitude were also observed during electrical stimulation of either the foot sole or the MG nerve, when stimuli were delivered at different hip angles. Foot sole stimulation resulted in facilitation of the H-reflex with the hip extended while depression of the reflex was recorded with the hip flexed. In contrast, MG nerve stimulation at group-I muscle afferent strength resulted in a significant increase in the Sol H-reflex magnitude with the hip flexed, while during hip extension, suppression of the H-reflex was present. This study provides evidence for the existence of a spinal mechanism, determined principally by the hip joint angle, which promotes switching between inhibitory and facilitatory pathways during hip flexion and extension. The origins of such a spinal mechanism are discussed.

Keywords Hip · H-reflex · Cutaneous afferents · Group I afferents · Human · Motor control

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Introduction

Considerable evidence derived from both animal and human experiments suggests that three types of afferent input to the spinal cord play a significant role in modulating reflex transmission during walking and stance. These afferent inputs include signals transmitting hip position, activation of ankle extensor muscle afferents and sensation from plantar cutaneous afferents. For example, during fictive locomotion in spinalized animals, the hip has to reach a certain extended position for the swing phase to be initiated (Anderson and Grillner 1981, 1983). Furthermore, the extensor muscles of the ankle must also be unloaded (Duysens and Pearson 1980).

Mechanical loading of the foot sole, ranging from 15 to 70 N, induces a significant inhibition of the Sol H-reflex, in both seated healthy human subjects and seated complete spinal cord injured patients (Knikou and Conway 2001). While low-threshold mechanoreceptors of the foot sole can influence Sol H-reflex excitability, static changes of the hip are also capable of modulating H-reflex excitability of distant limb muscles such as the soleus (Chapman et al. 1991). Collectively, there is considerable evidence that activation of cutanous afferents or of afferents registering changes in hip position can independently influence spinal reflex excitability. Studies describing the combined effects of these afferent inputs on spinal reflexes in humans have not been reported. Studies performed in decerebrate cats report that the hip position is important in initiating the stance to swing transition (Hiebert et al. 1996; Pearson and Rossignol 1991). Furthermore, a study performed in infants during

walking reports similar effects. In addition, an interaction between hip position and muscle loading has also been proposed to occur during walking (Pang and Yang 2000). The interaction between these two afferent signals was examined under different types of limb disturbances, permitting the evaluation of the above signals when they act together and/or separately. They suggested that it is not a specific value of hip extension or load before swing can be initiated; rather, it is the combination of these two factors (Pang and Yang 2000).

The observations regarding the effects of these afferent systems arise mostly from studies performed in reduced animal preparations during fictive locomotion (Hiebert et al. 1996; Kriellaars et al. 1994; Pearson and Rossignol 1991) or in infants during walking (Pang and Yang 2000). Because of the complex nature of walking, our present experiments were designed to examine the relative contributions of cutaneous, muscle, and joint signals on spinal reflex excitability in humans under more controllable static conditions. To examine changes in reflex excitability, the Sol H-reflex was used. Although studying H-reflex modulation is not automatically applicable to normal behavior (Andersen and Sinkjaer 1999; Kearney et al. 1999), it allows for an orderly examination on spinal reflex modulation.

In the present study, we investigated whether a combination of signals registering hip position, heteronymous muscle afferent activation and cutaneous afferent activation interact to influence the amplitude of the Sol H-reflex under static conditions. Our results indicate that the combination of these three afferent signals produces a substantial and rather unexpected change in H-reflex amplitude. In addition, when one or more of these signals is reduced or abolished, the reflex output is modified substantially. Part of this work has been reported in abstract form (Knikou and Rymer 2001a, 2001b).

Materials and methods

Twenty-six experiments in total were performed in 21 healthy adult human subjects. Experiments were conducted with IRB approval from the Northwestern University (Chicago, IL) and the informed consent of all participants. None of the subjects reported any history of neuromuscular or metabolic disease.

Subject position

Experiments were conducted with the subjects seated and supine. In the seated position (hip angle 120°, knee angle 160°, ankle angle 110°), both feet were supported by footrests while the effects of medialis gastrocnemius (MG) nerve and of plantar cutaneous afferent excitation on Sol H-reflex were investigated (see "Conditioning stimuli" below). With the subjects supine, the right lower limb was secured to a knee ankle foot orthosis brace (KAFO) constructed by the mechanical workshop of the Sensory Motor Performance Program (SMPP). Adjustments were made for shank and thigh lengths depending on the subject's height. The KAFO was connected to the motor head of an isokinetic dynamometer (Biodex Medical Systems, Shirley, NY). Ankle and knee joints were set at 110° (20° of plantar flexion) and 30° of flexion respectively. With the KAFO secured to the lower limb, the center of the subjects' hip joint was aligned with the center of the Biodex motor head. The hip joint was moved by the experimenter, in the sagittal plane.

H-reflex

The Sol H-reflex was elicited by stimulating the right posterior tibial nerve (PTN) at the popliteal fossa through a monopolar electrode (indifferent electrode placed above the patella) using a 1-ms pulse generated by a constant current stimulator (Digitimer, DS7A, UK) and triggered once every 5 s. Electromyograms (EMG) were recorded with a surface bipolar electrode (DelSys, USA) placed over the soleus muscle. The recorded EMG signals were amplified and band pass filtered (10–500 Hz) before being sampled at 1000 Hz and subjected to analog to digital conversion (PCI-MIO 16E, National Instruments Co., Austin, TX). The digitized EMG signals were rectified and the size of evoked M-waves and H-reflexes was measured as the area under the full-rectified waveforms (MatLab vs 5.3, Mathworks).

The susceptibility of the H-reflex to facilitation and/or inhibition is known to depend on its size (Meinck 1980; Crone et al. 1990). Accordingly, in the experiments examining the effects of hip angular variations on the Sol H-reflex, the stimulus strength was adjusted to give a control H-reflex equivalent to 15–30% of the maximal direct M-response (M-wave). This allowed a valid comparison to be made of the amount of facilitation/inhibition brought about by the conditioning stimuli between subjects. In addition, the M-wave size was used to monitor the consistency of stimulating and recording conditions (Boorman et al. 1996; Allison and Abraham 1994). By keeping the M-wave amplitude stable, the number of group-Ia afferent fibers recruited by the stimulus can be well controlled (Boorman et al. 1996). M-wave stability constituted a within subject factor. For example, when the M-wave of the reflex recorded at 30° of hip flexion was altered, the stimulus intensity was adjusted so that the size of the M-wave was of similar size to the M-wave recorded at 10° of hip flexion (control reflex in supine position). The M-waves recorded did not exceed 5% of the maximal M-wave (M_{max}) (see Fig. 2B).

In the experiments utilizing electrical conditioning stimuli (either plantar cutaneous afferents or medialis gastrocnemius nerve stimulation), the control Sol H-reflex (collected as 20 repeated responses) recorded at different hip angles tested (30°, 40° of flexion and 10° of extension) had the same amplitude as the control reflex in the supine position (10° of hip flexion) (see Fig. 1). These reflexes were equivalent to 15–30% of the maximal M-wave. The M-wave amplitude was used as a screening factor for

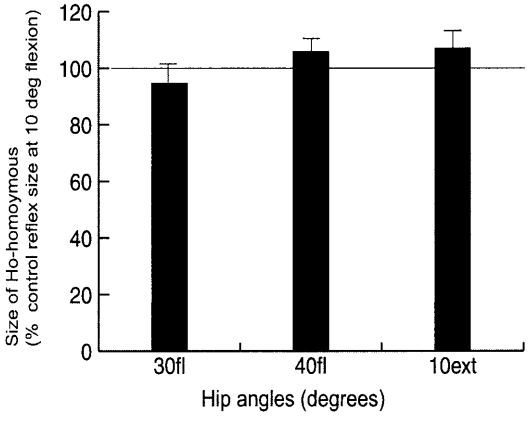

Fig. 1 Pooled data showing the average control reflex size ($Ho^{homonymous}$) recorded at 30° and 40° of hip flexion and at 10° of hip extension as a percentage of the mean control H-reflex size recorded at 10° of hip flexion; $P>0.05$ for all cases. *Error bars* indicate the SD of the average

accepting conditioned responses at each hip angle tested. For each unconditioned and conditioned H-reflex, 20 responses were collected and the mean size of both H-reflexes was estimated.

Conditioning stimuli (electrical)

Plantar cutaneous stimulation

The skin over the first to the third metatarsal joints was stimulated with a bipolar electrode placed transversely across the metatarsals. Using a constant current stimulator (model DS7A, Digitimer, UK), single shocks of increasing intensity were used to determine the perceptual threshold (PT). This was defined as the stimulus intensity first perceived by the subject. All subsequent conditioning stimuli were presented as trains of pulses graded with respect to PT and were equivalent to 3×PT. At 3×PT no movement of the intrinsic muscles of the foot could be elicited. Also, the stimulus intensities were not perceived as being painful, and therefore the evoked afferent volley involved mainly low-threshold afferents from mechanoreceptors of the foot. The conditioning stimulus train consisted of five pulses with an interstimulus interval of 4.8 ms (equivalent stimulation frequency 208 Hz) and a total pulse train duration of 24 ms. The conditioning stimulation train was repeated once every 5 s and preceded the H-reflex by variable delays. These delays were 0–9 ms, incremented in 3-ms steps (conditioning-test intervals) measured from the time to the last pulse in the conditioning stimulus train. Longer C-T intervals were not investigated as each experiment was set to last no more than 2 h while short-latency effects were investigated with both types of electrical conditioning stimulus. Conditioned Sol H-reflexes were recorded with the subjects seated as well as in supine position with hip positioned at different angles of flexion and at 10° of extension.

Heteronymous muscle afferents (MG nerve) stimulation

Methods for MG nerve stimulation used in the present study were similar to those described by Pierrot-Deseilligny and colleagues (1979, 1981b). The stimulus to the MG nerve was a single shock, 1 ms in duration, generated by a constant current stimulator (model DS7A, Digitimer, UK) and delivered with a bipolar electrode placed at a site where a clear contraction of the MG muscle could be seen. The stimulating electrode was placed at the lower and internal part of the popliteal fossa 6–10 cm below the cathode electrode to the PTN.

The stimulus strength to the MG nerve was expressed in multiples of motor threshold (MT) in the MG muscle. To avoid recurrent inhibition from gastrocnemius motoneurons to soleus motoneurons, the ipsilateral MG nerve was stimulated at 0.95×MT (Rossi et al. 1994). The magnitude of the MG stimulus was kept below the level that would generate an M-wave in the MG muscle (see Fig. 4B, MG stimulation alone). Surface electrodes (DelSys, USA) recording MG muscle activity were placed over the muscle site that showed contraction at minimal stimulus intensities. The effects of MG nerve stimulation on the homonymous muscle were observed online on a digital oscilloscope and were checked several times throughout the experiment to ensure that MG nerve stimulation did not evoke an M-wave on the MG muscle. EMG activity of vastus lateralis (VL), biceps femoris (BF) and tibialis anterior (TA) muscles was also recorded during MG nerve stimulation alone and during Sol H-reflex conditioning with MG nerve stimulation and with hip set at various angles. The ipsilateral MG nerve stimulation always preceded the PTN stimulation (H-reflex) at conditioning-test (C-T) intervals with varying delays (0–6 ms, incremented in 2-ms steps). Conditioned and unconditioned Sol H-reflexes were recorded with subjects in seated position as well as in supine position with hip positioned at various angles of flexion and at 10° of extension.

Experimental procedure

Static hip angle changes only

In eight healthy adult males (ages 22–35 years), we examined the effect of controlled angular variations of the ipsilateral hip joint on Sol H-reflex excitability. With the subjects seated, using a handheld monopolar electrode the optimum site for stimulating the PTN was estimated as the one that Sol Ia afferents could be selectively stimulated at low stimulus intensities. The monopolar electrode was then replaced by a permanent one (N-10-A, Medicotest, Denmark), inducing an H-reflex with identical behavior to the one observed with the monopolar electrode. After this procedure was completed, the lower limb was secured to the KAFO. With the subject in supine position and hip positioned at 10° of flexion, 20 reflex responses were recorded. This 10° reflex constituted the control reflex for the supine position, and was recorded at least twice in the course of each sequence to establish reflex stability and ensure that stimulus conditions remained unchanged. Reflexes recorded with the hip positioned at 20°, 25°, 30°, 40°, and 70° of flexion and at 10° of hip extension were considered as the conditioned reflexes. Conditioned and unconditioned H-reflex sequences were randomly alternated, since both reflexes are known to be depressed similarly by homosynaptic depression when the stimuli are randomly alternated (Pierrot-Deseilligny and Mazevet 2000).

Hip position changes combined with foot sole or MG nerve stimulation

In 13 healthy adult males (ages 20–35 years), we examined the effects of hip angle changes on Sol H-reflex excitability, combined with either ipsilateral foot sole cutaneous stimulation (five subjects tested) or with MG nerve stimulation. The ipsilateral foot sole and/or the MG nerve were stimulated in five conditions: the hip joint positioned at 10°, 30° and 40° of flexion, the hip extended at 10°, and in the relaxed seated position. First with subjects in seated position, the optimum stimulating site of the PTN was estimated as described above. In this position, the H-reflex was recorded (20 repeated responses) without any conditioning electrical stimuli and according to the H-reflex methodology employed in the current study. Reflexes conditioned with foot sole pulse train stimulation, applied at variable time delays (C-T intervals), were recorded in random order with the control reflexes.

The subject was then transferred to the supine position and the KAFO was attached to the lower limb. The hip joint was set at 10° of flexion passively by the experimenter and H-reflexes were recorded again (unconditioned and conditioned). The hip was then set to a new angle and reflexes were recorded again (with and without foot sole stimulation). At every hip angle tested (i.e., 30° hip flexion) the control reflex (20 repeated responses without conditioning electrical stimuli) was randomly alternated with the conditioned reflexes (H-reflex at 30° of hip flexion preceded by foot sole stimulation at variable time delays). In the course of each sequence the control reflex was recorded at least twice to establish reflex stability. The same experimental protocol was followed for the MG nerve stimulation, which was used as a conditioning stimulus to the Sol H-reflex with the hip positioned at various angles of flexion and at 10° of extension.

Data analysis

In the tests examining only the effects of static hip position changes on Sol H-reflex excitability, the conditioned reflexes were expressed as a percentage of the mean size of the control reflex (Ho; recorded at 10° of hip flexion). In the tests utilizing cutaneous plantar surface of the foot and/or MG nerve stimulation, again delivered at various angles of hip flexion/extension, the conditioned reflexes were expressed as a percentage of the mean size of the control reflex recorded at each tested hip angle ($Ho^{homonymous}$). A one-way analysis of variance (ANOVA) was applied to the experimental data sets. When statistical significance was encountered,

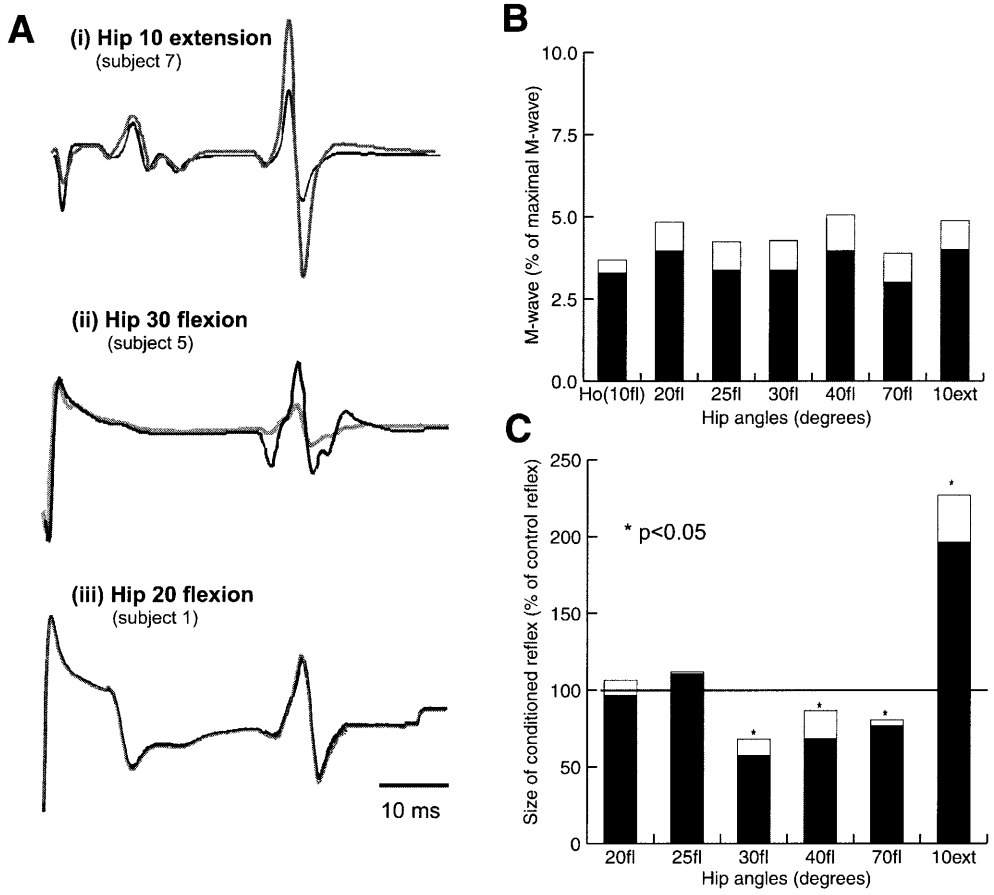

Fig. 2A–C Effects of controlled angular variations of hip joint on Sol H-reflex. The average H-reflex (n=20) recorded under control (*black line*) and with the ipsilateral hip set at 10° of extension (*gray line*) (**A***i*), with the hip set at 30° of flexion (**A***ii*) and with hip set at 20° of flexion (**A***iii*) for the three subjects tested is presented. Note that the inhibition and the facilitation in H-reflex amplitudes occurred without significant changes in M-waves. **B** Pooled data showing the size of the M-waves recorded with hip set at different angles of flexion/extension, expressed as a percentage of the M_{max} size. No significant differences in the M-wave size recorded at different hip positions was encountered (P=0.618). *Ho* represents the M-wave of the control reflex recorded at 10° of hip flexion. **C** Pooled data showing the effects of hip angular variation on the Sol H-reflex. For each hip angle tested, the average of the conditioned reflexes (as a percentage of the control H-reflexes recorded at 10° of hip flexion) was calculated for all subjects tested (n=8). The control H-reflex recorded at 10° of hip flexion was adjusted to 15–30% of the M_{max}. *Asterisks* indicate cases of statistically significant difference between the control and the conditioned reflex sizes (P<0.05). *The squares on the top of the histogram bars* **(B, C)** indicate the standard deviation of the average

post hoc Bonferroni tests for multiple comparisons were performed to determine which trial was significantly different from the other using P<0.05 as the criterion of statistical significance. The results are presented as mean values and standard deviation.

To assess the effects of MG and/or foot sole stimulation on Sol H-reflex amplitude having excluded the effects that static hip angle changes might have induced on spinal reflex excitability, a mathematical estimation of the afferent input modulation seen at different hip angles of flexion/extension was performed. Before evaluating the effects of electrical stimulation, we first subtracted the effect that the static change in the hip position induced. This analysis was performed for cases where no statistical difference was encountered between the $Ho^{homonymous}$ (30°, 40° hip flexion; 10° of hip extension) and the control H-reflex recorded at 10° of hip flexion (P>0.05). For example, the averages of $Ho^{homonymous}$ recorded at different hip angles, as percentages of the mean control reflex size recorded in supine position (10° hip flexion), are illustrated in Fig. 1. These $Ho^{homonymous}$ reflexes were used to normalize conditioned reflexes following MG nerve stimulation.

The modulation of heteronymous inhibition (MG nerve stimulation) at different ipsilateral hip joint angles is expressed as the difference reported in Eq. 1:

$$\text{Hcond/Ho (\%)-Hcond}^{\beta}\text{/Ho}^{homonymous}\text{ (\%)} \quad (1)$$

In this equation, Hcond/Ho (%) represents the H-reflex recorded at 30° and 40° of hip flexion and at 10° of hip extension without conditioning stimulus and expressed as a percentage of the control reflex recorded at 10° of hip flexion. $\text{Hcond}^{\beta}/\text{Ho}^{homonymous}$ (%) represents the H-reflex recorded at 30° and 40° of hip flexion and at 10° of hip extension, conditioned by either MG or foot sole stimulation and expressed as a percentage of the mean size of the homonymous control reflex ($Ho^{homonymous}$). A negative value of this equation might indicate a condition associated perhaps with the removal of the inhibitory effects on Sol H-reflex due to MG nerve stimulation. The modulation of cutaneous afferent input was estimated in the same way as the modulation of heteronymous inhibition.

Results

Effects of hip angle joint variations on Sol H-reflex size

In Fig. 2A the effects of controlled changes of the ipsilateral hip on the average H-reflex amplitude for three

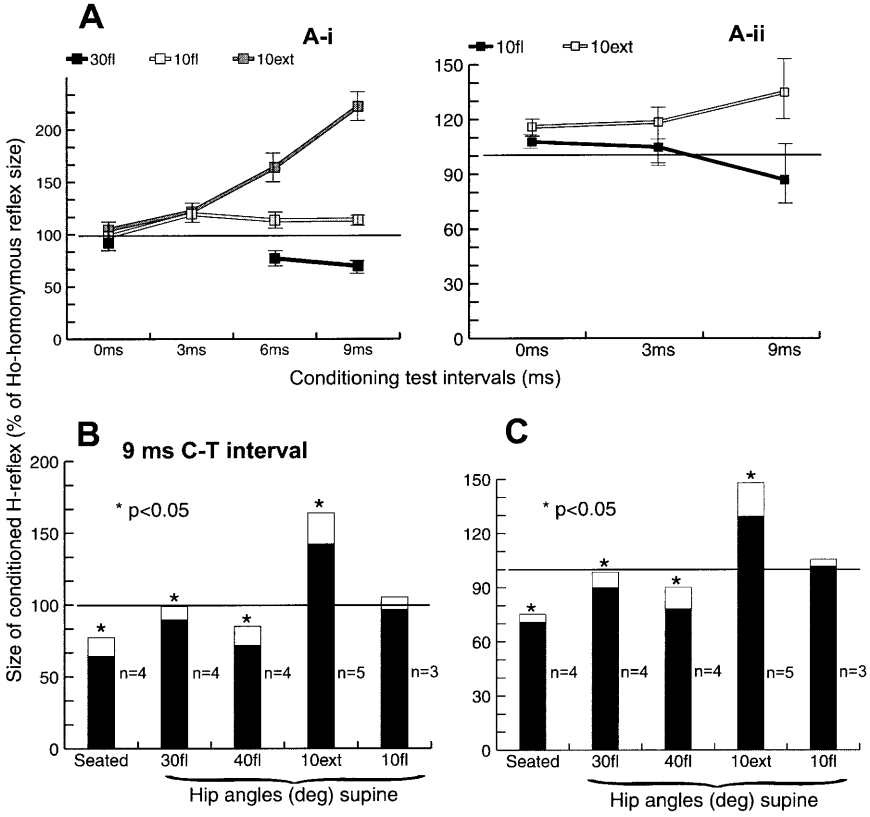

Fig. 3A–C Time course of the effect of stimulation of the plantar cutaneous afferents on the Sol H-reflex in two subjects tested (**A***i*) and (**A***ii*). The graphs show the average size of the conditioned H-reflex (as a percentage of the $Ho^{homonymous}$ control reflex size) as a function of the conditioning-test interval for each hip angle tested. See text for inhibitory or facilitatory effects. **B** Pooled data showing the effect of plantar cutaneous afferent stimulation at a 6-ms conditioning-test interval on the Sol H-reflex with subjects in seated position and with subjects in supine position with hip set at various angles of flexion and extension. Pooled data including all conditioning-test intervals and all subjects tested are shown in **C**. In both **B** and **C** the number indicated by *n next to each of the histogram bars* designates the number of subjects (out of five) in whom the conditioned reflexes were accepted according to the criteria presented in "Materials and methods." The control H-reflex for each hip angle was adjusted to 15–30% of the M_{max} and the conditioning plantar cutaneous afferent stimulation to 3×PT. For all hip angles tested, the average of the mean of the conditioned reflexes (as a percentage of the control H-reflexes; $Ho^{homonymous}$) was calculated. *Asterisks* indicate cases of statistically significant difference between control and conditioned reflex sizes ($P<0.05$). *The vertical bars and the white squares on the top of the histogram bars* designate the standard deviation of the mean

subjects tested are shown. In subject 7, extension of the hip to 10° resulted in a significant facilitation of the Sol H-reflex (gray line, Fig. 2Ai) with respect to the control reflex recorded at 10° of hip flexion (black line). In another subject tested, when the hip was positioned at 30° of hip flexion, there was a significant reduction of the H-reflex size (gray line) with respect to control values (black lines) (Fig. 2Aii). In contrast, 20° of flexion induced no significant changes in the H-reflex amplitude as shown in Fig. 2Aiii (data are from subject 1). All three cases of reflex conditioning occurred without any recorded changes in M-wave, characteristics demonstrating stable stimulation conditions. Figure 2B illustrates the average M-wave size of reflexes recorded at the control supine position and with hip positioned at different angles of flexion and extension, as a percentage of the maximal M-wave. One-way ANOVA showed no significant difference between the M-wave sizes recorded at each condition ($P=0.618$) verifying M-wave stability.

Hip flexion and extension resulted in significant changes in the size of the Sol H-reflex. The H-reflex size was reduced with the hip positioned at 30°, 40° and 70° of flexion, reaching overall amplitudes of 57.2±10.75% and 76.7±3.78% of Ho at 30° and at 70° of hip flexion respectively ($P<0.05$). No change in the size of the reflex was observed at 20° and at 25° ($P>0.05$) (Fig. 2C) of hip flexion, with the H-reflex reaching an overall amplitude of 96.52±9.83% of Ho at 20° of hip flexion. When the hip was set at 10° of extension, the H-reflex was significantly increased in comparison to control reflex values, reaching a mean level of 196.16±15.3% of control reflex values ($P<0.05$) (see Fig. 2C).

Effects of hip joint angle variations combined with plantar cutaneous or MG nerve stimulation

Ipsilateral plantar cutaneous stimulation

Figure 3Ai and Fig. 3Aii display representative examples of the effects following plantar skin stimulation on Sol

H-reflex amplitude for all the conditioning test intervals investigated. These effects are shown for two subjects tested (subjects 7 and 9) with hip positioned at different angles. For both cases the average size of the conditioned reflex is presented as a percentage of the $Ho^{homonymous}$. In Fig. 3Ai, plantar stimulation with hip positioned at 10° of hip flexion resulted in no significant changes in H-reflex amplitude, reaching an overall amplitude (all C-T intervals tested) of 111.3±5.15% of the $Ho^{homonymous}$ ($P>0.05$). In contrast, in the same subject plantar skin stimulation delivered with hip flexed at 30° induced a significant decrease in Sol H-reflex ($P<0.05$, for C-T intervals of 6 and 9 ms), reaching an overall amplitude of 79.11±11.25% of $Ho^{homonymous}$. Conversely, facilitation of the Sol H-reflex was observed when plantar skin stimulation was delivered with hip extended at 10°. This facilitation can be clearly seen in Fig. 3Ai, and is also related to the C-T interval, since at 0 ms the reflex size reached an amplitude of 104.62±3.16% of $Ho^{homonymous}$ ($P>0.05$), and at 9 ms the reflex reached an amplitude of 220±20.1% of $Ho^{homonymous}$ ($P<0.05$). In another subject tested (Fig. 3Aii), plantar cutaneous afferent stimulation with hip extended induced a significant facilitation of the H-reflex, reaching an amplitude of 134±5.61% of $Ho^{homonymous}$ at a 9-ms C-T interval. In this subject, plantar cutaneous afferent stimulation with hip set at 10° of flexion resulted also in no significant changes in the H-reflex size ($P>0.05$).

At 9 ms the reflex modulation appeared to be stronger, in comparison to the other C-T intervals investigated, for both body positions and hip angles studied (Fig. 3B). Plantar skin stimulation delivered at a 9-ms C-T interval with subjects supine and hip extended at 10° resulted in a significant increase in the magnitude of the Sol H-reflex, reaching an amplitude of 142.38±21% of control reflex values. In contrast, plantar skin stimulation delivered with subjects seated induced a significant inhibition, reaching an overall amplitude (all subjects tested) of 64.32±12.88% of $Ho^{homonymous}$ (Fig. 3B). The reflex inhibition appeared to be stronger with the subject in the seated position than that observed with the subject supine and with hip flexed at 30° and at 40°. It is conceivable that the observed reflex modulation could be attributable to differences in motoneuronal excitability between the supine and seated position.

A summary of changes (all C-T intervals tested) in H-reflex size following plantar cutaneous afferent stimulation with the hip positioned at different angles of flexion/extension and with subjects in seated position is presented in Fig. 3C. Plantar skin stimulation delivered with hip set at 40° and at 30° of hip flexion resulted in a significant decrease in the H-reflex size, reaching amplitudes of 80±5.9% and 90±4.24% of control reflex values respectively. Reflex depression was also observed with subjects in relaxed seated position, with the H-reflex reaching an overall amplitude of 70±2.2% of $Ho^{homonymous}$. Conversely, when the conditioning stimulus was delivered with hip extended at 10°, there was a significant increment in H-reflex size in all subjects tested, with an overall amplitude of 130±9.2% of $Ho^{homonymous}$. Figure 3 suggests an orderly relationship between the hip angle and the modulation (inhibition/facilitation) of the Sol H-reflex. The modulation of cutaneous effects tended to be facilitatory with the hip extended and inhibitory with the hip flexed. A linear regression analysis between reflex modulation and hip angle showed that $R^2=0.6234$, $P<0.0001$ ($y=-0.511x+9.3286$), supporting further the existence of an interaction between plantar cutaneous afferent activation and hip angle on reflex modulation.

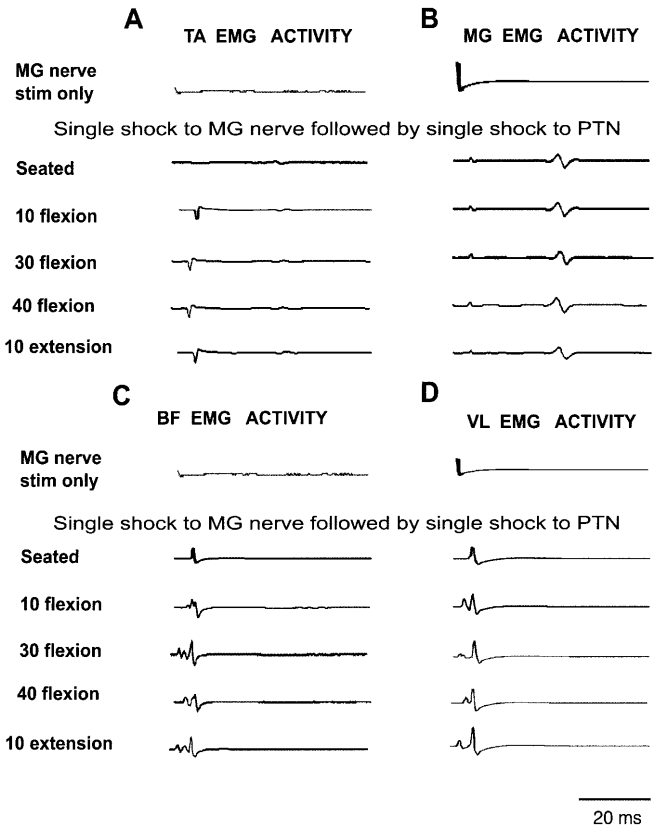

Fig. 4A–D EMG activity in TA, MG, BF and VL muscles is shown for one subject tested under two conditions. Firstly, EMG activity of each muscle is shown following MG nerve stimulation at 0.95×MT. Secondly, EMG activity of each muscle is shown following PTN stimulation preceded by ipsilateral MG nerve stimulation at a 6-ms C-T interval. Under both conditions, BF and VL muscles showed no activation, while MG displayed a small response which occurred at a latency corresponding to the Sol H-reflex

Electrical stimulation of the ipsilateral MG nerve

Figure 4 illustrates representative examples of EMG activity of the lower limb muscles, such as VL, BF, TA and MG recorded at different hip angles following MG nerve and/or MG-PTN stimulation, in one subject tested. In all cases, no EMG activity was observed in the BF and VL muscles (Fig. 4C, D). In addition, EMG activity of MG muscle (Fig. 4B), represented as a waveform corre-

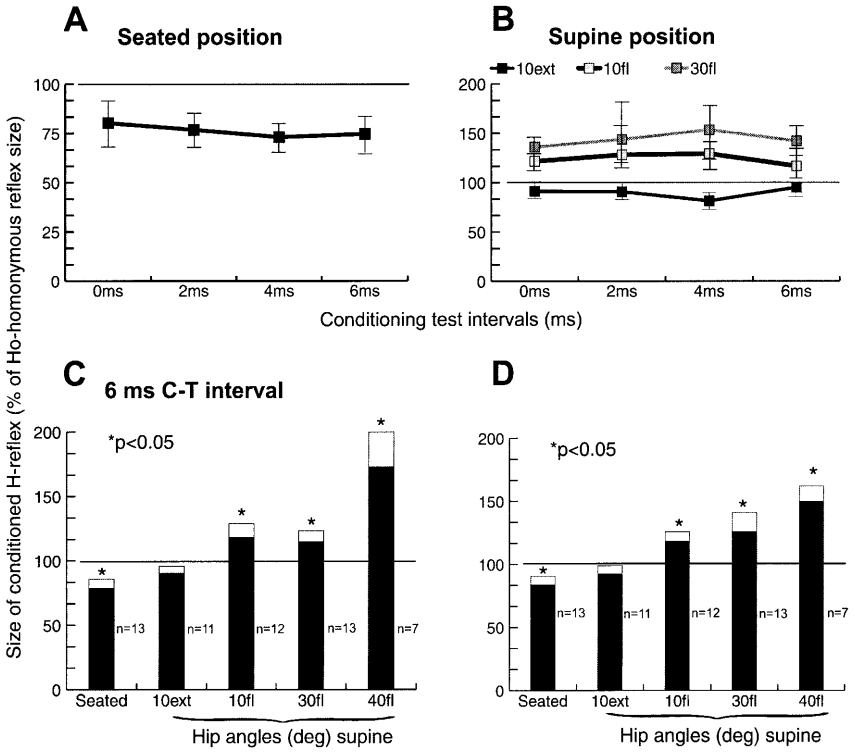

Fig. 5 **A** Pooled data (all subjects tested) showing the effect of MG nerve stimulation on the Sol H-reflex with subjects in seated position. The control reflex was adjusted to 15–30% of the M_{max} and the conditioning MG nerve stimulation was adjusted to 0.95×MT. For each conditioning-test interval, the average of the mean of the conditioned reflexes (as a percentage of the control H-reflex) was calculated for all the healthy human subjects tested. *Error bars* designate the SD of the average. **B** Time course of the effects of the MG nerve stimulation on the Sol H-reflex with subjects in supine position and hip set at 10° of extension, 10° of flexion and 30° of flexion. The graphs show the size of the conditioned H-reflex (as a percentage of the control reflex size; $Ho^{homonymous}$) as a function of the conditioning-test interval for each hip angle tested. The $Ho^{homonymous}$ was adjusted to be of similar size to the control reflex recorded at 10° of hip flexion. **C, D** Pooled data showing the effects of MG nerve stimulation, at a 6-ms conditioning-test interval **(C)** and including all conditioning-test intervals **(D)** on the Sol H-reflex with subjects in seated position and in supine position with hip positioned at various angles of flexion/extension calculated. In both graphs **(C, D)** the number indicated by *n next to each of the histogram bars* designates the number of subjects (out of 13) in whom the conditioned reflexes were accepted according to the criteria presented in "Materials and methods." *Asterisks* indicate statistically significant differences between the conditioned H-reflex size and the control H-reflex, $Ho^{homonymous}$ (P<0.05). SD of the average is designated by *the white squares on the top of the histogram bars in* **C** *and* **D**

sponding to the latency of the Sol H-reflex, was present in cases where the PTN stimulation was preceded by MG nerve stimulation (6-ms C-T interval).

Based on the MG EMG activity, it is likely that a number of MG group-I afferents were excited following PTN stimulation, while no motor axons were stimulated. MG nerve stimulation alone induced no M-wave of either the MG muscle (Fig. 4B) or the soleus muscle (data not shown). Furthermore, TA muscle was not active in any of the different positions tested. It can therefore be assumed that heteronymous effects from dorsiflexor muscles did not contribute to the observed reflex modulation.

Ipsilateral MG nerve stimulation with subjects in seated position resulted in a significant depression of the Sol H-reflex (Fig. 5A). The Sol H-reflex reached an overall amplitude (all subjects tested) of 80±8.13% of $Ho^{homonymous}$ at 0 ms and 75±5.81% of $Ho^{homonymous}$ at a 6-ms C-T interval. This indicates that the reflex depression was stronger at 6 ms than that observed at a 0-ms C-T interval. This finding is in agreement with other studies reporting maximal Sol H-reflex inhibition at a 5- to 6-ms C-T interval following MG nerve stimulation (Pierrot-Deseilligny et al. 1979). In only one of the subjects tested (data not shown) was the reflex inhibition observed at 0- and 6-ms C-T intervals not statistically significant different (P=0.667).

Similarly, MG nerve stimulation delivered with subjects supine and hip set at various angles of flexion and extension resulted in significant changes in the size of the Sol H-reflex (Fig. 5B). MG nerve stimulation with hip set at 30° of flexion resulted in facilitation of the reflex. The reflex reached an overall amplitude of 136.04±13.34% of $Ho^{homonymous}$ at a 0-ms C-T interval, while at 6 ms it reached an overall amplitude of 141.97±15.97% of $Ho^{homonymous}$. Similarly, reflex facilitation was the only effect following MG nerve stimulation with hip flexed at 10°. The reflex amplitude varied between 120% and 130% of $Ho^{homonymous}$. In contrast, MG nerve stimulation with hip extended at 10° resulted in no significant changes in H-reflex, reaching amplitudes of 91±12.1% of control reflex values at 0 ms and

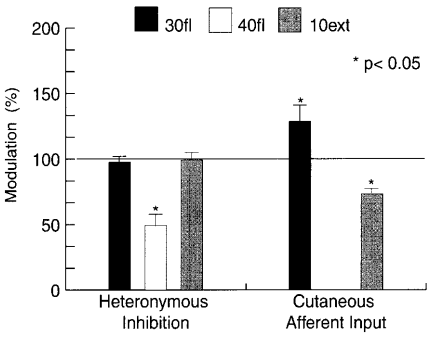

Fig. 6 The estimated modulation of heteronymous inhibition and of plantar cutaneous afferent input with hip positioned at 30° and 40° of flexion and at 100° of extension is plotted *on the abscissa*. A decrease in modulation is presented with values that are below 10°, while an increase in modulation is presented with values that are above 100°. For both cases, the modulation was estimated based on Eq. 1. The modulation of heteronymous inhibition (from MG nerve to Sol Ia afferents) was not significant for hip positioning at 30° of flexion and at 10° of extension (P>0.05). *Asterisks* indicate cases where a significant modulation of heteronymous inhibition and of cutaneous afferent input was encountered. *The error bars* designate the standard deviation of the average

95±11.5% at a 6-ms C-T interval (P>0.05). With hip extended, no significant difference between the H-reflex sizes recorded at the C-T intervals investigated was encountered (P=0.879) (see Fig. 5B).

Based on the finding that the reflex depression is stronger at a 6-ms C-T interval, data from all subjects were grouped together and the mean average for that C-T interval presented in the histogram bar shown in Fig. 5C. It is clear that as the hip flexion angle is increased, the facilitation of the reflex is also increased, reaching an overall amplitude of 170±12% of homonymous control reflex values at 40° of hip flexion. In opposition to hip flexion, hip extension resulted in no significant changes in the size of the H-reflex, with an overall amplitude of 90±5.3% of $Ho^{homonymous}$ (P=0.098). The summary changes in H-reflex size (all subjects tested and all C-T intervals) are presented in the histograms in Fig. 5D. It is evident that changes in the Sol H-reflex amplitude following MG nerve stimulation depend on the hip angle.

Modulation of muscle and cutaneous afferent effects with changes in hip angle

Figure 6 illustrates the estimated modulation of cutaneous afferent input and of heteronymous inhibition at various hip positions using Eq. 1 ("Materials and methods"). A decrease in modulation of cutaneous afferent input (–26.65±5.17, P<0.05) was observed with hip set at 10° of extension while an increase (+28.48±10.52, P<0.05) was observed with the hip positioned at 30° of flexion. A decrease in modulation of the heteronymous inhibition from MG to Sol H-reflex was observed with hip positioned at 40° of hip flexion (–50.75±11.18%), while for hips positioned at 30° of flexion the modulation was decreased only by –0.85±6.7 (see Fig. 6). At 10° of hip extension no significant modulation of heteronymous inhibition was present (P>0.05).

Discussion

In this study we have established that afferent actions on soleus α-motoneurons display sharp variations, depending on the position of the hip joint. The results can potentially be explained by a neural mechanism, presumably of spinal origin, which promotes graded switching between excitatory and inhibitory pathways during transitions from hip flexion to hip extension and vice versa. In addition, we also determined that ipsilateral plantar cutaneous stimulation and group I muscle afferent activation result in significant changes in H-reflex excitability, depending on the position of the ipsilateral hip.

Effects of controlled variations of hip joint angle

Under static conditions, positioning of the hip joint in flexion resulted mainly in depression of the Sol H-reflex, while placing the hip in 10° of hip extension resulted in a significant facilitation in the H-reflex size (Fig. 2C). It is conceivable that these changes are an expression of changes in motoneuronal excitability arising during controlled hip angular variations, although we are not in a position to distinguish motoneuronal effects from changes in the effects of afferent pathways (i.e., presynaptic mechanisms).

The amplitude of the Sol H-reflex is known to be strongly modulated during human walking and running primarily because of cyclical changes in H-reflex excitability arising as part of the locomotion cycle (Capaday and Stein 1986; 1987). Sol H-reflex excitability appears to increase in the latter part of the stance phase (Crenna and Frigo 1987) in parallel with the Sol EMG, which is also the point at which the ipsilateral hip is extended.

Changes in hip position are known to induce H-reflex modulation under static conditions in humans (Chapman et al. 1991). Although some of the results reported in the above study are partly in agreement with our current results, a similar pattern of reflex modulation with hip extended was not observed. However, a different methodology for stabilizing the lower limb was employed and comparisons between studies could be potentially misleading.

Based on the results of the present study, we propose that hip flexion has inhibitory effects on Sol H-reflex amplitude while hip extension has facilitatory effects. The afferent mechanisms responsible are uncertain, although both joint and muscle afferents warrant evaluation. Joint afferents of the knee are known to exert significant effects on motoneuron excitability in decerebrate cats (Baxendale and Ferrell 1981, 1985) and on reflex pathways that act on distal joints. In addition, static an-

kle angle variations in healthy human subjects induce a significant H-reflex modulation (Robinson et al. 1982). Although the present results are consistent with the significant role that hip position plays during locomotion in humans and in reduced animal preparations, the current data should be interpreted cautiously with respect to studies performed in humans during walking, since the two conditions differ significantly. The current study provides evidence that different hip positions can powerfully influence and modulate spinal reflex excitability in man, although the pathways responsible may not be identical with those described in reduced animal preparations.

Effects of plantar cutaneous stimulation and hip position changes

The present study verifies the major impact of plantar cutaneous afferents on spinal reflex pathways in man. Plantar cutaneous afferent activation induced a depression of the Sol H-reflex, both when subjects were seated and when supine with hip flexed. Conversely, a facilitation of the reflex was observed with subjects in supine position and hip extended.

Studies addressing the effects of sural nerve (a pure sensory nerve) on Sol H-reflex excitability have shown that stimulation of low-threshold sensory afferents induces an early inhibition, but this is then followed by a substantial facilitation of the H-reflex (Delwaide et al. 1981). This facilitation is attributed to decreased presynaptic inhibition of Sol group Ia afferents (Iles 1996). We did not observe this type of reflex modulation perhaps because we were stimulating plantar skin. An interaction between cutaneous afferents and Ib afferents on spinal interneurons has been postulated in man (Pierrot-Deseilligny et al. 1981a). It is conceivable that excitation of low-threshold plantar cutaneous afferents induced Sol H-reflex modulation mediated by the Ib inhibitory interneurons.

Our current results are in agreement with studies reporting Sol H-reflex inhibition following activation of low-threshold cutaneous afferents of the foot in both relaxed seated healthy subjects and in complete spinal cord injured human subjects (Knikou and Conway 2001; Wood et al. 1998). Low-threshold plantar afferent excitation introduced with the hip positioned at different angles had either inhibitory or facilitatory effects, depending on the hip angle. As the hip flexion was increased the reflex depression was also increased (see Fig. 3B, 3C). Potential mechanisms include presynaptic inhibition of the Ia afferent terminals exerted by cutaneous fibers (Iles 1996), inhibition of α-motoneurons mediated by cutaneous input to Ib inhibitory interneurons (Pierrot-Deseilligny et al. 1981a) and cutaneous inhibition of α-motoneurons via segmental interneuron effects. At present we have no evidence to support any of these mechanisms preferentially. Future experiments will attempt to explore possible mechanisms in more detail.

The demonstration that activation of plantar cutaneous afferents can increase the Sol H-reflex amplitude with the hip extended, and inhibit the reflex with the hip flexed, suggests the presence of a neural 'switch' during controlled hip angular variations. We suggest that the net afferent actions from the leg muscles are shifted between inhibitory and excitatory motoneuronal and/or interneuronal populations, depending on the position of the hip.

Effects of group I extensor afferent stimulation with hip flexed or extended

MG nerve stimulation resulted in inhibition of the H-reflex with subjects in relaxed seated position. It is likely that the inhibition of group I afferents from the MG onto Sol Ia afferent terminals is evoked mainly from tendon organ (Ib) afferents (Pierrot-Deseilligny et al. 1981b; Gritti and Schieppati 1989), although Ia afferents may also participate. Maximal depression of the Sol H-reflex occurred at a 6-ms C-T stimulus interval. In the current study, the depression of the H-reflex was quite variable perhaps because a stronger excitatory contribution from the Ia afferents of the MG to the Sol might be present in some subjects. However, our findings are in agreement with other studies addressing disynaptic heteronymous inhibitory effects of group I extensor muscle afferents (Pierrot-Deseilligny et al. 1981b; Gritti and Schieppati 1989) since in seated position, MG nerve stimulation induced only inhibitory effects with the maximal depression observed at a 6-ms C-T interval.

MG nerve stimulation delivered with the hip joint set in extension resulted in no significant effects on the H-reflex, while nerve stimulation delivered with hips flexed induced a significant increase in H-reflex amplitude. Presumably the differences between MG and Sol lie in the fact that the gastrocnemius muscle may also function as a knee flexor, and contribute to flexion withdrawal during excitation of various cutaneous and muscular afferents. A decrease in the modulation of heteronymous inhibition was found with hip flexed at 40° (see Fig. 6), which was perhaps responsible for the removal of the Ib inhibitory effects observed with subjects in seated position (Fig. 5). Furthermore, based on the lack of concurrent EMG activity in BF, VL and TA muscles, heteronymous effects arising from activity in the main hip flexor/extensor muscles and ankle dorsi flexors can be excluded.

It is conceivable that the observed effects on the Sol H-reflex induced by MG nerve and by plantar cutaneous afferent stimulation might also be related to the positions of the body (seated and supine). Changing the body position from sitting to supine could induce a change in composition of the afferent volley generated by inputs from several joint, muscle and skin receptors. However, transcranial cortical magnetic stimulation (TMS) induces two separate phases of H-reflex facilitation with subjects in supine and in seated position (Goulart et al. 2000), suggesting that these body positions do not influence differ-

ently the reflex excitability. In addition, throughout the experiment head and trunk were kept stable, while the reflexes were recorded after the lower limb was positioned to a new hip angle by the experimenter. However, it is possible that vestibular influences might have contributed to the reflex modulation observed at different body positions following both types of conditioning electrical stimuli.

To conclude, the current study provides evidence for modulation of heteronymous group-I inhibition and cutaneous afferent input which is under the influence of static hip angle changes. Therefore, changes in hip position have the potential to change the motor output of distant muscles and in addition to influence neuronal pathways such as the group I non-reciprocal pathway.

Functional significance and concluding remarks

Controlled angular variations of the ipsilateral hip joint combined with plantar cutaneous afferent activation and/or extensor group-I muscle afferent stimulation can powerfully modulate the Sol H-reflex excitability in humans. Afferent actions from the lower limb are evidently switched depending on the position of the hip, indicating that position of the hip is a controlling factor of spinal reflex excitability. Adequate stimulation and proper timing in excitation of these afferents with adequate positioning of the hip may be useful in rehabilitation techniques for the management of reflex induced extensor or flexor hypertonicity. Further studies examining the involved neuronal mechanisms under static conditions are needed. Furthermore, the observed combined effects will be of significant value to be studied in patients with a complete motor and sensory paralysis. This will further support that in the observed reflex modulation neural reflex pathways of segmental origin are involved.

Acknowledgements M.K. was supported by a research grant (H133P990006) from the NIDRR, USA. The authors wish to thank Professors J.D. Brooke, C.J. Heckman and J.R. Rosenberg for their valuable comments on earlier versions of the manuscript.

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