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Decrease of spasticity with muscle vibration in patients with spinal cord injury

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HIGHLIGHTS

- Vibratory stimuli of 50 Hz over the rectus femoris induced a significant decrease in clinical and neurophysiological measures of spasticity in SCI patients.
- Measures of spasticity reveal significant different temporal evolution for complete and incomplete SCI.
- Vibration might be a useful coadjuvant tool in the rehabilitation of spasticity in SCI patients.

ABSTRACT

Objective: Spasticity is common after spinal cord injury (SCI). Exaggerated tendon jerks, clonus, and spasms are key features of spasticity that result from hyperexcitability of the stretch reflex circuit. Here we studied the effects of vibration on the rectus femoris muscle (RF) on clinical and electrophysiological measures of spasticity in the leg.
Methods: Nineteen SCI patients with spasticity and nine healthy subjects were studied at baseline and under stimulation (vibration at 50 Hz during 10 min on the thigh). Neurophysiological studies included evaluation of the soleus T wave and Hmax/Mmax ratio. Clinical measurements of spasticity were the score in the Modified Ashworth Scale (MAS), range of motion (ROM), and duration and frequency of clonus.
Results: Patients with incomplete SCI (iSCI) presented higher number of cycles and longer duration of clonus than patients with complete SCI (cSCI). The Hmax/Mmax ratio and T wave amplitude at baseline were significantly larger in iSCI patients than in cSCI or healthy subjects. During vibration, we found a significant reduction of MAS and duration of clonus, and an increase in ROM, in all patients as a group. The Hmax/Mmax ratio and the T wave amplitude decreased significantly in both, patients and controls.
Conclusions: Prolonged vibration on proximal lower extremity muscles decreased limb spasticity in patients with spinal cord injury, regardless of whether the lesion is complete or incomplete.
Significance: Muscle vibration may be useful for physical therapy, by facilitating passive and active movements of the extremities in spastic SCI patients.

1. Introduction

Spasticity is one of the most invalidating conditions of the upper motor neuron syndrome (Maynard et al., 1990; Levi et al., 1995a,b; Johnson et al., 1998; Skold et al., 1999). It is usually defined as a velocity-dependent increase in muscle tone, and presents with exaggerated tendon jerks, clonus, and spasms, which result from hyperexcitability of the stretch reflex (Lance, 1980; Adams et al., 2007; Elbasiouny et al., 2010). Finding methods to control such excitability enhancement has therapeutic interest. Several studies have demonstrated reduced inhibition of the H reflex by vibratory stimuli in spastic patients (Ashby et al., 1974; Ongerboer de Visser et al., 1989). In fact, vibration may cause not only a decrease in the soleus H reflex (Calancie et al., 1993), but also produce changes beyond the segmental level. In patients with spinal cord injury (SCI), Butler et al. (2006) found vibration-induced reduction of withdrawal reflex activity without changes in the size of the H reflex and suggested the possible clinical applicability of vibration to reduce the involuntary reactions of leg muscles. Vibration has been commonly applied to the tendon of soleus or tibialis anterior muscles (Burke and Ashby, 1972; Ashby et al., 1974; Ongerboer de Visser et al., 1989; Calancie et al., 1993; Butler et al., 2006). However, empirical observations during

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our clinical practice showed that some patients felt that spasticity in their legs reduced when vibration was applied over the ipsilateral quadriceps muscle belly. In fact, it is known that large muscle afferents from the quadriceps have an inhibitory effect on homonymous and heteronymous monosynaptic reflexes that is due to either presynaptic effects (Meunier et al., 1993; Faist et al., 1994) or, more likely, to post-activation depression of alpha motoneurons (Crone and Nielsen, 1989). There are previous studies on the effect of tendon vibration (Ageranoti and Hayes, 1990; Butler et al., 2006) in patients with spinal cord injury, but little is known about the effects of segmental vibration applied over the muscle belly (Paoloni et al., 2010). Therefore, we carried out a systematic study of the effects of local vibration applied over the quadriceps muscle belly on clinical and electrophysiological measures of spasticity in SCI patients.

2. Patients and methods

The study was carried out in 19 patients with SCI and in 9 age-matched healthy subjects. Patients were selected according to the following inclusion criteria: (1) stable SCI, (2) lesion level above T12, (3) lower limb spasticity $\geqslant 1.5$ according to the Modified Ashworth Scale (MAS), (4) presence of soleus H reflex, (5) stable medical treatment during the last 2 weeks, (6) absence of joint limitation that prevented movement. Demographic and clinical characteristics of the patients are summarized in Table 1. The spinal cord lesion was cervical in 13 patients and thoracic in the remaining 6 patients. According to American Spinal Cord Injury Association Impairment Scale (ASIA) (Marino et al., 2003), nine patients presented ASIA A, nine ASIA C, and one ASIA D. The mean age of control subjects was 33.8 ± 9.4 years, ranging from 23 to 48 years, and that of the patients was 36.0 ± 10.6 years, ranging from 18 to 67 years (Mann–Whitney U test; $p = 0.7$). The mean time since SCI was 5.6 ± 1.9 months (Table 1).

The procedure was approved by the ethics committee of the Institute Guttmann, according to the declaration of Helsinki and all patients and healthy subjects signed a consent form.

2.1. General procedure

The study protocol included two conditions: baseline and stimulation. All subjects were submitted to clinical and neurophysiological evaluations in both conditions. During the stimulation condition, vibration was applied with an electric vibration device (Wahl Powerssage 4300, Clipper Co., Illinois, USA) at a frequency of 50 Hz during 10 min over the rectus femoris (RF) muscle. The apparatus was fastened with ribbons around the thigh, over the belly of the RF. All the evaluations in the stimulation condition were carried out while vibration was ongoing for, at least, 10 min.

2.2. Clinical evaluation

Baclofen treatment was washout at least 12 h before the clinical and neurophysiological evaluations in patients who were under oral baclofen treatment.

The clinical and neurophysiological evaluation was performed while sitting on a comfortable chair. For clinical evaluation, we used the modified Ashworth Scale (MAS) for the knee (Bohannon and Smith, 1987), and the Range of Motion (ROM), tested at V3 fast stretch velocity of the modified Tardieu scale, up to the first catch for knee extension, which reflects resistance to stretch (Boyd and Graham, 1999). While the patient was sitting, one examiner extended the knee passively with a fast movement, while another examiner recorded the angle at which the joint had the first catch with a manual goniometer fixed with tape at the knee. The complete knee extension was considered 0°. The response to stretch (*clonus*) was examined after inducing a sudden manual stretch of the triceps surae muscle by applying maximal strength in the manoeuvre. A linear accelerometer (model 348720; Bionic Iberica S.A., Barcelona, Spain) was attached to the dorsum of the foot for clonus recording (Fraix et al., 2008), which was sampled at 5 kHz, amplified, filtered (0.1–50 Hz) and stored for off-line analysis on a personal computer equipped with the software package Acknowledge MP100 (Biopac Systems, Goleta, CA, USA). The recording window was 50 s. The manoeuvre was repeated five times to obtain a mean value.

2.3. Electrophysiological evaluation

We used routine electrodiagnostic equipment (Synergy, Oxford Instruments; Surrey, England) to perform the following tests in patients sitting with the knee and ankle joints flexed at 90°.

Hmax/Mmax ratio: For the soleus H reflex study, subjects had bipolar Ag–AgCl surface recording electrodes (0.8 cm diameter and 2.0 cm fixed interelectrode distance) attached to the skin overlying the soleus muscle. The stimulating electrodes (1 ms rectangular pulse) were attached to the popliteal fossa over the

Table 1
Demographic and clinical characteristics of SCI patients. ASIA, American Spinal Cord Injury Association (ASIA) Impairment Scale; MAS, Modified Ashworth Scale; M, male; F, female; Neurological injury level C, cervical; Th, thoracic.

Age	Sex	Injury level	AIS	Time since injury (months)	Aetiology	Initial MAS	Antispastic medication
30	M	C6	A	4	Trauma	3	–
22	F	Th9	A	3	Trauma	2	–
50	M	C5	A	4	Trauma	2	–
20	M	Th9	A	6	Trauma	2	–
48	M	C6	A	8	Trauma	3	–
28	M	C5	A	5	Trauma	2	–
28	M	C6	A	5	Trauma	2	–
50	F	C4	A	4	Trauma	2	Baclofen
18	M	C7	A	9	Trauma	1.5	–
29	M	Th8	C	7	Myelitis	2	Baclofen
32	M	Th4	C	6	Trauma	3	Baclofen
55	M	C3	C	8	Trauma	3	Baclofen
28	M	Th11	C	9	Myelitis	2	–
42	M	Th6	C	6	Trauma	4	Baclofen
20	M	C5	C	4	Trauma	2	Baclofen
50	M	C6	C	4	Trauma	3	–
60	M	C6	C	4	Trauma	1.5	–
67	F	C5	C	4	Trauma	2	–
26	M	C4	D	6	Trauma	1.5	–

posterior tibial nerve. The maximum amplitude of the H reflex (Hmax) was determined by using as many stimuli as needed at stimulation steps of 0.2 mA around the intensity eliciting the largest amplitude of the H reflex. The maximum amplitude of the M wave (Mmax) was determined as the size of the response to a stimulus of supramaximal intensity. The EMG signal was amplified (1 mV/D) and band-pass filtered (2–10,000 Hz).

T wave: The T wave was obtained with the same recording electrodes as for the Hmax/Mmax ratio after tapping with a sweep-triggering hammer (Kawe reflex hammer Trömner, Germany) over the Achilles tendon in five recordings.

2.4. Data analysis

We measured the peak to peak amplitude of Hmax, Mmax and Twave, and calculated the Hmax/Mmax ratio. For the clonus, we measured the number of cycles and total duration of clonus. A cycle was defined as a sinusoidal wave of an amplitude larger than 50 μV. Results are expressed as mean ± standard deviation (SD).

To analyse the clinical and neurophysiological data according to severity of SCI, patients were divided in two groups according to the ASIA classification: complete SCI group (cSCI), including patients with ASIA A, and incomplete SCI group (iSCI), including patients with ASIA C and D. Statistical analyses were performed with the SPSS 13.0 software. The Wilcoxon signed rank test was used to compare data from baseline and stimulation conditions in patients and control subjects, while the Kruskal–Wallis (for multiple comparisons) and Mann–Whitney *U* test (for two groups comparison) were used to compare data between groups. The level of statistical significance for all comparisons was set at $p \leqslant 0.05$.

3. Results

3.1. Effects of vibration on clinical parameters of spasticity

During vibration there was a significant reduction in MAS measured at the knee joint (Wilcoxon test, $p < 0.001$), a significant increase in ROM for knee extension (Wilcoxon test, $p = 0.001$) and a significant reduction of the number of cycles and the total duration of clonus, as shown in Fig. 1 (Wilcoxon test, $p \leqslant 0.006$ for the two comparisons).

3.2. Effects of vibration on results of neurophysiological tests

Representative recordings of T wave (T wave), H and M wave, at baseline condition (A) and during vibratory stimulation (B) were shown in a patient with incomplete SCI at Th4 level in Fig. 2.

In the baseline condition, the Hmax/Mmax ratio in patients was not significantly different from healthy controls (Mann–Whitney *U* test; $p = 0.20$). Hmax was not different in SCI patients in comparison to healthy controls (Mann–Whitney *U* test; $p = 0.1$). However, Mmax was significantly smaller in SCI patients with respect to controls ($p = 0.006$).

Vibration induced a significant reduction of Hmax/Mmax ratio in the control group (Wilcoxon test, $p = 0.005$) and in the SCI patients ($p = 0.001$). Vibration did not cause any changes in the Mmax amplitude in any group (Wilcoxon test, $p \geqslant 0.65$ for each group). The percentage change of Hmax/Mmax ratio between stimulation and baseline, expressed as percentage of the values in the baseline condition, showed no statistically significant differences between control subjects (32.0 ± 19.1%) and patients (43.1 ± 32.8%) (Mann–Whitney *U* test; $p = 0.217$).

3.3. T wave

The mean amplitude of the T wave in baseline condition in patients was not different from that in control subjects (Mann–Whitney *U* test; $p = 0.7$) (Table 2). Vibration induced a significant inhibition of the T wave in both SCI patients and healthy control subjects (Wilcoxon test; $p = 0.002$ and $p = 0.007$, respectively).

3.4. Differences between complete and incomplete SCI

In baseline condition, patients with iSCI did not differ from those with cSCI in MAS and ROM (Mann–Whitney *U* test; $p = 0.35$ and $p = 0.88$, respectively) but the evaluation of clonus revealed a significantly higher number of cycles and longer total duration in iSCI than in cSCI (Mann–Whitney *U* test; $p < 0.02$ for both comparisons).

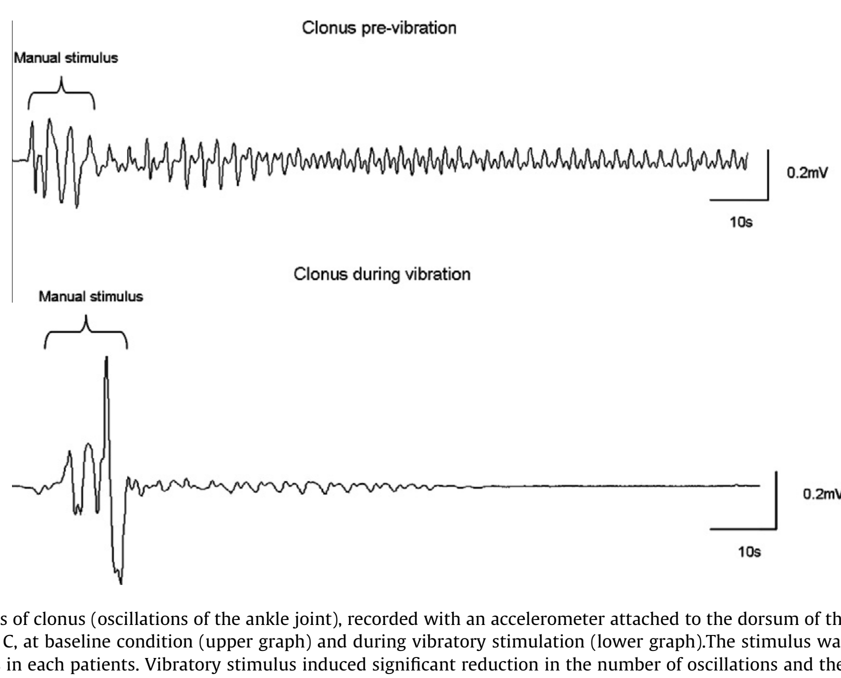

Fig. 1. Representative recordings of clonus (oscillations of the ankle joint), recorded with an accelerometer attached to the dorsum of the foot, in a patient with spinal cord injury at thoracic level T8, ASIA C, at baseline condition (upper graph) and during vibratory stimulation (lower graph).The stimulus was a manual stretch of triceps surae, which was repeated three times in each patients. Vibratory stimulus induced significant reduction in the number of oscillations and the duration of clonus with respect to baseline condition (pre-vibration) in this patient.

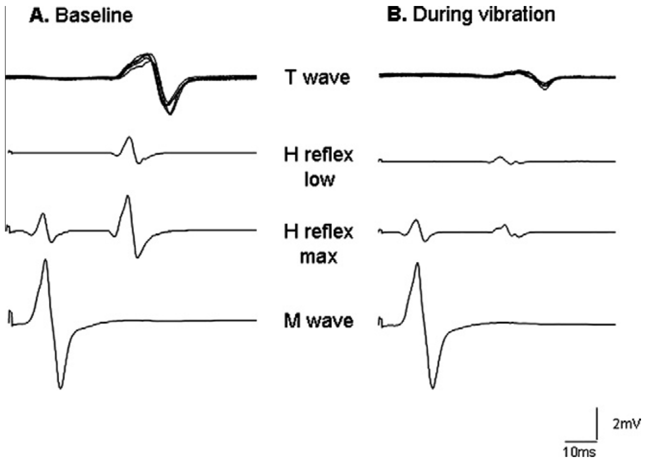

Fig. 2. Representative recordings of T wave (average of T wave), H wave at low electrical intensity (H reflex low), H wave at the intensity appropriate to elicit an H reflex of maximum amplitude (H reflex max), and M wave, at baseline condition (pre-vibration) (A) and during vibratory stimulation (B) in a patient with incomplete SCI at Th4 level. The maximum amplitude of the H reflex (Hmax) was determined by using as many stimuli as needed at stimulation steps of 0.2 mA around the intensity eliciting the largest amplitude of the H reflex. The maximum amplitude of the M wave (Mmax) was determined as the size of the response to a stimulus of supramaximal intensity. Vibratory stimulus induced significant reduction in T wave and H wave, but not in M wave.

There was a similar reduction in the MAS score and in the increment of ROM in the cSCI and iSCI groups during vibration, with no statistically significant differences between them (Mann–Whitney *U* test; $p > 0.3$ for all comparisons). The number of cycles and duration of clonus were reduced significantly with vibration in the iSCI group (Wilcoxon test: $p = 0.008$ for both comparisons), while there were no significant differences between conditions in the cSCI (Wilcoxon test, $p = 0.3$ for both comparisons) (Table 2).

The minimal electrical stimulus intensity inducing Hmax was similar in both cSCI (8.4 ± 1.2 mA) and iSCI (7.3 ± 1.6) (Mann–Whitney *U* test; $p = 0.54$). The Hmax/Mmax ratio and the T wave amplitude in baseline were significantly larger in iSCI than either cSCI or control groups (Mann–Whitney *U* test; $p < 0.004$ for all comparisons) (Fig. 3 and Table 2). The Hmax/Mmax ratio and the T wave showed no significant differences between cSCI and the control group (Mann–Whitney *U* test; $p > 0.7$). However the Hmax and Mmax were significantly smaller in cSCI than in iSCI (Mann–Whitney *U* test; $p = 0.03$ vs. $p = 0.04$, respectively) and control subjects (Mann–Whitney *U* test; $p = 0.03$ vs. $p = 0.0001$, respectively). In iSCI, the Hmax was not different with respect to control subjects (Mann–Whitney *U* test; $p = 0.7$), but Mmax was significantly smaller (Mann–Whitney *U* test; $p = 0.05$).

The percentage reduction of the Hmax/Mmax ratio with vibration was significantly more marked in cSCI patients and control subjects than in iSCI patients (Mann–Whitney *U* test; $p = 0.02$, for each comparison), but there were no differences between cSCI and control groups (Mann–Whitney *U* test; $p = 0.8$).

4. Discussion

The results of this study show that vibration at 50 Hz applied on the quadriceps muscle produces a significant decrease in clinical measures of spasticity in the ipsilateral leg of SCI patients. The clinical changes were accompanied by measurable neurophysiological changes with significant reduction of Hmax/Mmax ratio and T wave. In addition, we found that iSCI patients presented higher excitability of these reflexes than the cSCI patients in baseline con-

Table 2
Mean and standard deviation of clinical and neurophysiological data according to the condition (baseline; stimulation) in all spinal cord injury (SCI) patients lumped as a group, patients with complete SCI (cSCI), patients with incomplete SCI (iSCI) and healthy subjects. *p*-Value according to Wilcoxon signed rank test. Bold values means $p \leqslant 0.05$ (significant differences).

	All patients			Patients with cSCI			Patients with iSCI			Healthy subjects		
	Baseline	Stimulation	*p*	Baseline	Stimulation	*p*	Baseline	Stimulation	*p*	Baseline	Stimulation	*p*
MAS	2.2 ± 0.6	1.1 ± 0.6	**<0.001**	2.1 ± 0.6	1 ± 0.7	**0.007**	2.2 ± 0.6	1.2 ± 0.5	**0.003**	–	–	–
ROM	−36.7 ± −23.6	−17.9 ± −16.5	**0.001**	−34.0 ± −24	−16.2 ± −14.8	**0.02**	−35.7 ± −25.3	−17.5 ± −18.7	**0.008**	–	–	–
Hmax	2.4 ± 1.8	1.3 ± 1.4	**<0.001**	1.6 ± 1.0	0.6 ± 0.8	**0.003**	3.2 ± 2.1	2.2 ± 1.6	**0.05**	3.7 ± 1.7	1.2 ± 1.0	**<0.001**
Mmax	5.1 ± 2.8	5.2 ± 2.8	**0.1**	4.0 ± 1.4	4.0 ± 1.5	**0.97**	6.3 ± 3.4	6.5 ± 3.4	**0.13**	10.0 ± 2.2	9.8 ± 2.6	**0.58**
Hmax/Mmax ratio	0.5 ± 0.2	0.3 ± 0.2	**0.001**	0.4 ± 0.1	0.1 ± 0.1	**0.005**	0.6 ± 0.2	0.4 ± 0.2	**0.01**	0.4 ± 0.27	0.13 ± 0.1	**0.005**
Twave (mV)	1.8 ± 1.3	1.1 ± 0.9	**0.002**	0.9 ± 0.6	0.5 ± 0.4	**0.008**	2.7 ± 1.1	1.6 ± 1	**0.008**	1.7 ± 1.2	0.8 ± 0.8	**0.007**
Clonus												
Duration (s)	20.7 ± 20.7	7.2 ± 11.3	**0.006**	1.9 ± 3.4	2.0 ± 3.5	0.3	31.1 ± 18.6	10 ± 13.3	**0.008**	–	–	–
Number of oscillations	113.3 ± 118.6	38.1 ± 58.9	**0.004**	9.2 ± 18.4	8.3 ± 15.3	0.3	171.2 ± 110.2	54.7 ± 68.3	**0.008**	–	–	–

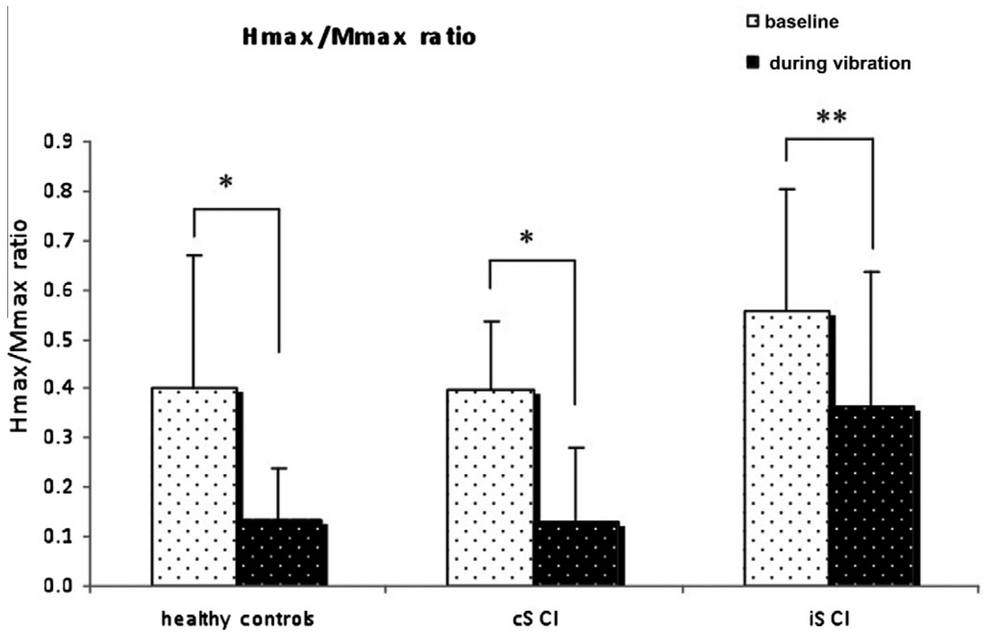

Fig. 3. Hmax/Max ratio recorded at baseline condition and during 10 min of vibratory stimulation in the healthy controls, in patients with incomplete spinal cord injury (iSCI) and complete SCI (cSCI). Each bar shows mean and standard deviation of Hmax/Mmax ratio. $^{*}p \leqslant 0.002$; $^{**}p = 0.006$ comparison between baseline and vibratory stimulation condition for each group. The percentage reduction of the Hmax/Mmax ratio with vibration was significantly more marked in cSCI patients and control subjects than in iSCI patients (Mann–Whitney *U* test; $p = 0.02$, for each comparison), but no differences between cSCI and control groups (Mann–Whitney *U* test; $p = 0.8$).

dition. Reduction in Hmax/Mmax ratio during stimulation was less marked in the iSCI group than in the cSCI and in control groups.

4.1. Effects of vibration

By applying a vibratory stimulus of 50 Hz on the RF in patients with cSCI and iSCI, we observed a decrease in Hmax/Mmax ratio and T wave in both groups. The mechanisms by which vibration induces inhibition of the H reflex have been elucidated thanks to the works of various authors. It was once considered that the continuous bombardment of impulses in the Ia fibres activated the so called primary afferent depolarization neurons, which act at a presynaptic level in the afferent Ia terminals to the alpha motoneuron (Rudomin, 1990; Nielsen et al., 1995). However, although the theoretical concept of presynaptic inhibition remains useful (Rudomin, 2009), mechanisms of post-activation depression and dendritic depolarization are prevalent nowadays as the most likely explanation for the decrease of the H reflex during vibration (Burke et al., 1989; Abbruzzese et al., 2001; McNulty et al., 2008). Vibration-induced H reflex inhibition was found in subjects with SCI (Schindler-Ivens and Shields, 2004; Ongerboer de Visser et al., 1989). In our study, we confirmed that there was a different effect of vibration in SCI patients that paralleled the severity of the lesion, with more effect in the cSCI than in the iSCI patients, but reduced in both.

The heteronymous effect on the soleus H reflex by vibration over the quadriceps muscle could be due to monosynaptic bidirectional projections between the soleus and RF muscles (Meunier et al., 1993; Faist et al., 1994). Therefore, by applying vibratory stimulation to the RF, there is activation of interneurons by Ia pathways, which might inhibit the soleus reflex response. However, a mechanical spread of the vibration, causing activation of muscle spindle primary endings in the soleus muscle cannot be entirely ruled out (Faist et al., 1994).

There are several other possibilities which might explain the changes induced by vibration on soleus Hmax and T wave. Vibration activates the Ia fibres at a frequency that renders them unresponsive to other inputs, a phenomenon known as "busy-line" (Bove et al., 2003). In this condition, a stretch that would activate the same fibres may not work. An example of this situation is the reduction in the duration of the clonus during vibration (Hidler and Rymer, 2000). Activation of the quadriceps group I afferents (Ia and Ib) may also induce reciprocal and homonymous inhibition at the motoneuronal level (Pierrot-Deseilligny, 1990). These effects can be reproduced in an heteronymous muscle circuitry such as the one for the soleus, since there is a strong connection between the spinal interneurons mediating thigh and leg muscles afferents (Meunier et al., 1993). In fact, an effect from quadriceps muscle afferents on soleus motoneurones has been reported in humans for electrical stimulation (Meunier et al., 1996) as well as for tendon taps (Cheng et al., 1995). Activation of Ib inhibitory pathways from the quadriceps exerts inhibitory effects on soleus motoneurons demonstrated also in humans (Rossi et al., 1999). Additionally, in our experiment, we cannot exclude of the possibility that vibration activates afferents from other muscles such as knee flexors, which effects have been studied less than those of quadriceps.

We used clinical scores to observe the effects of vibration on the antagonist muscle (MAS and ROM). As can be observed from the results of our study, joint angles of knee extension significantly increased, with improvement on MAS and ROM. This could actually be due to a reciprocal inhibitory effect of vibration on the antagonist muscle while the agonist one undergoes an enhancement of activity because of the tendon vibration reflex. Ageranoti and Hayes (1990) reported similar results when applying vibration on wrist extensor muscles in hemiparetic patients, showing a facilitation of the agonist muscle activity and inhibition of the antagonist.

4.2. Differences between complete and incomplete spinal cord injured patients

In our study, clonus revealed a significantly higher number of cycles and longer total duration in iSCI, which decreased with vibratory stimulation. Many authors have suggested that clonus occurs as a result of a self-reexcitation of hyperactive stretch reflexes (Hidler and Rymer, 1999; Beres-Jones et al., 2003). Nakazawa et al. (2006) concluded that the stretch reflex is overexcitated in the iSCI patients, and clonus could be more excitable in subjects with iSCI that cSCI. However, further studies are needed to analyse the characteristics of clonus in complete and incomplete SCI.

In our study, obvious neurophysiological differences were observed between subjects with complete and incomplete SCI since 3–9 months following injury. The Hmax was significantly smaller in cSCI than in iSCI patients and in healthy controls, but no differences were detected between iSCI and healthy controls. However, we cannot exclude the long term duration effect of oral baclofen on the Hmax in iSCI (Table 1). It has been reported that cSCI patients present increasing H reflex responses in the spinal shock phase, manifested by increase of the Hmax/Mmax ratio and a decrease of the Mmax from 2 to 6 months in comparison to a few days after SCI (Hiersemenzel et al., 2000). Calancie et al. (1993) observed significantly smaller Hmax and Mmax and a significant increase in the Hmax/Mmax ratio in chronic SCI (iSCI + cSCI) with respect to healthy subjects. In contrast, Schindler-Ivens and Shields (2004) did not find significant changes in the Hmax in chronic cSCI compared to healthy subjects. On the other hand, Nakazawa et al. (2006) reported that Hmax and Mmax were not different with respect to healthy subjects in chronic iSCI patients (from 12 months post-injury), but they were significantly reduced in chronic cSCI (Nakazawa et al., 2006).

These variations suggest that modulation of spinal reflexes has a different temporal evolution for complete and incomplete SCI. In our study, neurophysiological assessments were performed in subjects 3–9 months following SCI. The Mmax in the cSCI group was decreased in amplitude compared to the iSCI group, possibly due to reduced muscle fibre size by disuse (Hiersemenzel et al., 2000; Nakazawa et al., 2006) or to the loss of lateral corticospinal tracts leading to a degraded function of interneuronal circuits (Nakazawa et al., 2006). After the loss of supraspinal control in cSCI, the remaining input from peripheral receptors may differentially affect the function of motoneurons and interneurons (Dietz and Müller, 2004). In addition to disuse and muscle atrophy in SCI, the other authors suggested a loss of synaptic input and lack of activation of the spinal motor neurons following central disconnection as a part of the decrease in Mmax in lower-leg muscles, which become functionally inactive (Van De Meent et al., 2010). Dysfunction of these anterior horn cells may result in a disturbance of axonal flow, leading to axonal degeneration (Van De Meent et al., 2010). Impaired axonal transport secondary to functional disturbance of spinal motor neurons may then lead to dysfunction of neuromuscular transmission at the motor endplate and a subsequent decrease in Mmax amplitude (Chang, 1998). Finally, depending on the severity of SCI, it is logic to expect more reduction in Mmax in cSCI than in iSCI.

In contrast, our iSCI subjects showed an increment in the excitability of the spinal reflex activity measured by Hmax/Mmax ratio and T reflex with respect to healthy subjects. Probably, as noted by some authors (Little and Halar, 1985; Little et al., 1999; Calancie et al., 2004), spinal monosynaptic reflexes change over time, increasing first and then decreasing at about the fourth month following SCI. However, the high Hmax/Mmax ratio can express rather a decrease of Mmax (as found here) than a pure increase in reflex excitability (Dietz and Colombo, 2004).

Experimental studies have also shown that reflex facilitation (studied by the Hmax/Mmax ratio) was higher after partial lesion than after complete transection of the spinal cord in the rat (López-Vales et al., 2006). One possible explanation was brought by Lee et al. (2005), who studied differences between groups of rats with SCI of various degrees of severity and suggested that the absence of supraspinal connections in complete lesions allowed the H reflex to regain some sensitivity to afferent stimulus frequency. However, when the supraspinal connections were partially damaged, there was a decrease of the modulation of the H reflex that generates a disruption in the mechanisms of inhibition. Indeed, sensory inputs from peripheral nerves have been shown to reduce the excitability of spinal motoneurons in standing subjects, an inhibitory effect that was increased in clinically complete SCI patients compared with healthy subjects (Kawashima et al., 2003).

5. Conclusion

Despite the differences between cSCI and iSCI patients, prolonged vibration on the proximal leg muscles produced a significant decrease of spasticity in the whole limb. Thus, vibration might be a useful coadjuvant tool in the rehabilitation of spastic SCI patients during passive mobilization and also during gait training (Paoloni et al., 2010). Further studies are needed to determine, among other aspects, whether the effect of vibration continues after termination of the stimulus, for how long it may last, and whether or not it involves non-stimulated extremities.

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