Effect of Electrical Stimulation of Hamstrings and L3/4 Dermatome on Gait in Spinal Cord Injury

Arjan van der Salm, MSc, PT* ▪ Peter H. Veltink, PhD† ▪ Hermie J. Hermens, PhD*,† ▪ Anand V. Nene, MD, PhD* ▪ Maarten J. IJzerman, PhD, PT*,†

*Roessingh Research Development, Enschede and †Biomedical Signals Systems, University of Twente, Enschede, The Netherlands

■ **ABSTRACT**

Objective. To determine the effect of electrical stimulation of hamstrings and L3/4 dermatome on the swing phase of gait.

Materials and Methods. Five subjects with incomplete spinal cord injury (SCI) with spasticity were included. Two electrical stimulation methods were investigated, i.e., hamstrings and L3/4 dermatome stimulation. Both interventions were applied during the swing phase of gait. The main outcome measures were step length, maximum hip, and knee flexion during the swing phase of gait. In three subjects changes of spinal inhibition during gait were evaluated using the Hoffman reflex/m (motor)–wave (H/M) ratio at mid swing.

Results. The hip flexion decreased 4.6° ($p < 0.05$) when the hamstrings were stimulated during the swing phase, whereas the knee flexion was not changed. The step length did not change significantly. One subject showed a decrease of the H/M ratio to a nonpathologic level during hamstrings stimulation.

Conclusion. It was concluded that hamstrings stimulation during the swing phase results in a reduction of the hip flexion in all five SCI subjects. The H/M ratio of the vastus lateralis was normalized using hamstrings stimulation in one of three subjects. Stimulation of the L3/4 dermatome provides no significant changes in gait performance, but in one subject the H/M ratio increased. ■

KEY WORDS: electrical stimulation, gait, H-reflex, muscle spasticity, spinal cord injuries

INTRODUCTION

An important gait impairment in patients with spinal cord injury (SCI) is decreased knee flexion during the swing phase (1,2). This impairment can cause a limitation of the swing limb advancement of the affected leg, which will decrease the step length of that leg. It is thought that spasticity may play an important role in this impairment (1,3). In particular, activities of the vastus lateralis and rectus femoris are reported to limit knee flexion (2). To assist patients with SCI to improve their gait, electrical stimulation (ES) can be used. Several studies found positive effects of using ES in patients with SCI (4–10). One study also included stimulation of the hamstrings combined with the use of an orthosis to enhance the knee flexion (11). In normal gait, hamstrings are only activated

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at the end of the swing phase to decelerate the knee extension (12). The knee flexion during swing is induced passively due to an active hip flexion and the push off initiated by the calf muscles. In patients with SCI, the knee flexion might be actively provoked during the swing phase using stimulation of the hamstrings. This also may affect the movement of the hip because the hamstrings are bi-articular muscles.

Functional ES is mainly used to achieve a direct force production in the muscles. But functional ES also will induce neurophysiologic changes that may influence the gait. Inhibition of spastic muscles may be one of these effects. This mechanism was investigated in a study of the effect of cutaneomuscular stimulation on soleus H-reflex (3). It was found that the H-reflex of the soleus muscle can be inhibited by cutaneomuscular stimulation of the plantar side of the foot. Another study found that stimulation of the peroneal nerve can inhibit the triceps surae stretch reflex in stroke patients (13). Both studies used 3–5 pulses of 1 msec at a frequency of 200 Hz. In contrast, in studies in which ES is used clinically, the pulses are approximately 300 μsec and the frequency ranges from 20 to 25 Hz for muscle stimulation (4,5,7,14–16).

The goal of this study was to determine the effect of hamstrings and L3/4 dermatome stimulation, which is used clinically, on the inhibition of the vastus lateralis (H/M ratio during mid swing) and on the gait parameters (hip and knee flexion during swing and step length). Stimulation was executed during swing phase of gait. The effect could be very useful in the treatment of patients with SCI, especially when spastic muscles are inhibited.

METHODS

Subjects

Subjects were recruited from a rehabilitation center in the Netherlands (Het Roessingh, Enschede). Only subjects with incomplete SCI for at least 6 months were included. Subjects were only included if they were able to walk with or without support or orthosis and if their gait was affected by spasticity, which was determined using electromyogram (EMG) measurement during gait. For this, the EMG of six muscles (soleus, gastrocnemius, tibialis anterior, rectus femoris, vastus lateralis, and hamstrings) in the leg was measured. Thereafter, outcomes were analyzed by an experienced Physical Medicine and Rehabilitation (PMR) physician. All subjects gave informed consent to participate in the experiment, which was approved by the local ethics committee.

Design

Subjects were assessed two times on separate days. Both days started with a baseline measurement followed by an intervention measurement. Each baseline measurement consisted of six trials, during which kinematic measurements were performed, and at least five trials, during which the H-reflex was measured. For each trial subjects walked 10 m. A test stimulus for the H-reflex was applied during one randomly chosen gait cycle in each trial.

After the baseline measurement, the intervention measurement was performed. All measurements, kinematic and H-reflex measurements, were executed again combined with one of the interventions. Antagonist muscle (hamstrings) was stimulated on one day; dermatome stimulation (L3/4 dermatome) was performed on the other. The sequence, however, was randomized. Each day, the time at which the measurements started was kept the same. The most affected leg of the subjects was used for the measurements.

Interventions

Self-adhesive electrodes (5×9 cm) were used to stimulate hamstrings or dermatome. Two electrodes were placed proximally and distally over the muscle belly of the hamstrings, covering both the semitendinosus and biceps femoris. For dermatome stimulation one lateral electrode was placed just proximal from the femoral epicondyl and the other electrode was placed medially just distal from the head of the tibia (17). This placement covered part of the L3/4 dermatome. In addition, the medial electrode stimulated the sensory saphenous nerve (L3/4). The stimulation frequency was 30 Hz for both the muscle and dermatome stimulation. A biphasic block pulse was used with a pulse width of 300 μsec for muscle stimulation and 100 μsec for skin stimulation. The intensity of muscle stimulation was adjusted to allow the knee to bend against gravity in sitting position for at least 20°. The stimulation intensity was controlled for its effect in upright position. In this position, with the stimulated limb hanging freely, the knee had to bend also for at least 20°. The intensity of the dermatome stimulation was just below the motor threshold.

In both interventions the stimulation burst started at the onset of swing phase and lasted for 70% of the swing phase. The timing of the burst was controlled by an angular-velocity sensor (gyroscope), which measured angular velocity in the sagittal plane (18). This gyroscope was fixated on the proximal head of the fibula with a strap. An individual threshold was used to detect the onset of the swing phase.

Measurements

Kinematics

A Vicon® (Oxford metrics Ltd., Oxford, UK) setup (version 370, six cameras) was used to measure the kinematics during gait. Passive markers were placed on the sacrum (S1) and on the left and right anterior superior ilea, lateral thighs, lateral knee rotation axis, lateral lower legs, lateral malleolli, and head of the second metatarsal bones according to a strict protocol. These markers were placed by an experienced physical therapist. The VCM (Vicon Clinical Manager, version 1.37) model was used to determine maximal knee and hip flexion in the sagittal plane and step length (19).

EMG Recording

The EMG of the vastus lateralis muscle was measured with surface electrodes (Neuroline® type 720 00-S Ag-AgCl gel electrodes: Medicotest, Ølstykke, Denmark; diameter 12 mm, interelectrode space 20 mm) using a bipolar arrangement. A ground electrode was applied on the ipsilateral lateral malleolus. The muscle electrodes were applied at 1/3 of the line from the lateral side of the patella to the anterior spina iliaca superior (20). Before application, the skin was shaved, abraded, and cleaned with alcohol. For the Porti 16-5 ASD EMG recording TMSI® hardware and software (TMS International, Enschede, The Netherlands) was used. The sample frequency of the EMG was 2048 Hz with a high pass filter of 5 Hz and a digital Finite Impulse Response (FIR) low pass filter of 553 Hz.

H-reflex Measurement

In order to stimulate the femoral nerve, the active electrode was placed in the femoral triangle and the counter electrode was applied on the ipsilateral gluteal area (21). A monophasic 500 µsec block pulse was used to stimulate the nerve. The optimal stimulation location of the nerve was found by using a handheld probe. For optimal stimulation condition, the active electrode was pushed down in the tissue using a soft ball (diameter 1.5 cm), which was secured by a strap around the thigh. Before the measurements during gait were performed, the H-reflex was measured in supine position. The M-wave and H-reflex started at certain delays after the stimulus artifact, depending on the leg length of the subjects. The peak-to-peak values in the EMG signal were calculated for both the M-wave and the H-reflex. The stimulation intensity was increased with steps of 2–5 mA until saturation of the M-wave was found, which was defined as M_{max}. During all measurements it was tried to keep the M-wave response at 10% of the M_{max} by adjusting the amplitude. M-waves less than 5% or more than 20% of the M_{max} were excluded (21). Test stimuli were given at 80% of the gait cycle, corresponding to mid swing (12). The timing of the test stimulus was controlled by a gyroscope. The responses to at least five successful stimuli were determined.

The H-reflex amplitudes during the swing phase were related to the M_{max} by calculating the H/M ratio using the following equation (22):

$$\text{H/M ratio} = H_{10\%-M_{max}}/M_{max}$$

Statistical Analysis

The changes in the step length, maximum knee and hip flexion were analyzed using a nonparametric test for paired data (Wilcoxon signed rank test). The level of significance was defined as 5%.

To be able to indicate which H/M ratios are within a normal range and which are pathologic, a reference range for the H/M ratio was calculated. For this, data of healthy subjects, which were published in another study, were used (22). The reference range or interval was calculated for a two-tailed probability of 0.05 and the number of subjects was 10. Values that are not included in this reference range were defined as pathologic.

Table 1. Demographic Data and Baseline Values of the Maximum Knee and Hip Flexion and H/M Ratio During Swing of the Subjects. ASIA D Means That All Subjects Were Incomplete Subjects With SCI

Subject no.	Gender	Age	ASIA	Injury level	Time since injury (months)	Modified Ashworth scale (Quadr.)	Knee flexion (°)	Hip flexion (°)	H/M ratio
1	F	57	D	C5/6	111	2	38.3	20.0	0.22
2	M	51	D	C5/6	20	3	31.5	33.4	0.47
3	M	56	D	C4/5	60	2	38.7	23.1	
4	M	34	D	C4/5	75	1+	62.9	23.7	0.48
5	M	63	D	T4	40	3	24.1	25.3	

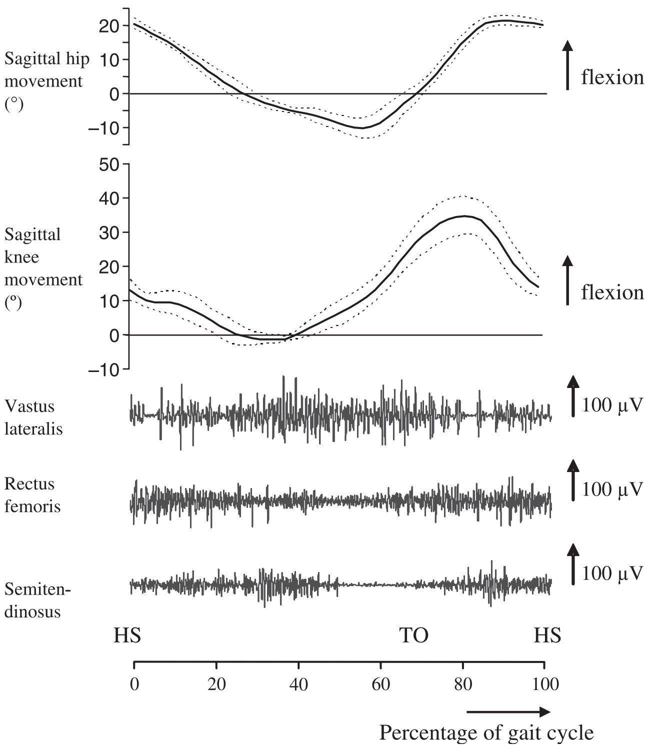

Figure 1. Example of the kinematic data and EMG signals during one stride. The data are derived from subject 1. The movements of the hip and the knee in the sagittal plane are presented. Below, the EMG signals of the vastus lateralis, rectus femoris, and semitendinosus are shown. HS is heel strike and TO is toe off.

Statistical analysis was performed using SPSS 11.50 (2002) software.

RESULTS

Five subjects with SCI participated in the study. The demographic data and the baseline values are presented in Table 1. The age of the subjects with SCI ranged from 34 to 63 years. All subjects had incomplete (ASIA D) cervical spinal cord lesions and their time since injury was from 20 to 111 months. The Modified Ashworth scale (MAS) (23) of the quadriceps ranged form 1+ to 3. Except one, all subjects showed decreased flexion of the knee during the swing phase at the investigated side. This was accompanied with an increased EMG activity of the vastus lateralis in all subjects.

Figure 1 shows kinematic and EMG data of a baseline measurement of one subject. The maximum hip flexion was 22° and the maximum hip extension was –8°. The knee angle ranged from –2° at stance to 34° at swing. The EMG shows activity throughout the whole cycle for the vastus lateralis and rectus femoris. The semitendinosus muscle is only silent just before toe off.

In Figure 2 the individual outcomes of the gait performance are presented. Subject 2 shows a reduced step length of approximately 20% when hamstrings are stimulated. This is accompanied with a reduced hip flexion. In addition, subject 4 also has a reduced hip flexion during swing.

The kinematic outcomes of the whole group are shown in Figure 3. No significant changes were found in the step length. The knee flexion showed also no significant change. The hip flexion during hamstrings stimulation was significantly smaller than the baseline measurement (change of 4.6°, $p < 0.05$).

The reference range of the H/M ratio at 80% of the gait cycle (mid swing) in healthy subjects was found to be 0 to 0.29.

Figure 4 shows the results of the H/M ratios of three subjects during rest and mid swing for the baseline and intervention measurement. In the other two subjects the H-reflex could not be measured properly. In one subject the femoral nerve could not be stimulated and in the other subject no M-wave could be detected.

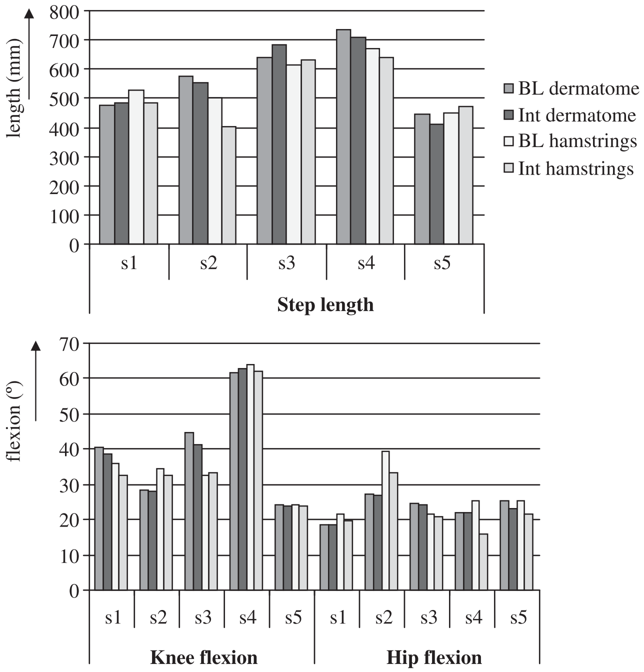

Figure 2. Individual results of the gait performances: step length, maximal knee flexion, and maximal hip flexion during swing. s is subject, BL is baseline session, and Int is intervention session. The interventions are stimulation of the hamstrings or L3/4 dermatome. Before each intervention measurement a baseline measurement was performed.

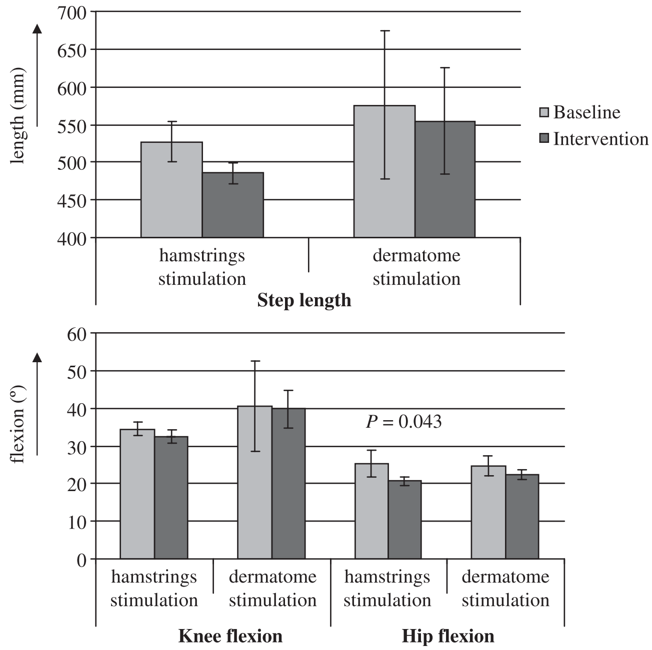

Figure 3. Gait parameters step length, hip flexion, and knee flexion in spastic subjects with spinal cord injury (medians and 25 percentiles). In the upper graph the step length is presented. In the graph below the maximum knee flexions and hip flexions are presented. The *p*-value is derived from a Wilcoxon signed rank test.

The figure shows that the average M-waves (stock graphs) remain approximately 0.1 (10% of M_{max}). The dotted line in the graph is the upper bound of the reference range (22). The H/M ratio of subject 1 at dermatome stimulation increases from within the reference range to a value, which exceeds the reference range. For subject 2 the baseline measurement at the hamstrings stimulation exceeds the reference range (H/M ratio is 0.41), whereas the H/M ratio during stimulation lies within this reference range (H/M ratio is 0.16). In this subject the H/M ratio was increased during the dermatome stimulation. In subject 4 almost no change of the H/M ratios due to one of the interventions was present.

DISCUSSION

The results indicate that inhibition of the vastus lateralis due to stimulation of the hamstrings may occur in FES applications. This effect might be useful in the treatment of spastic muscles during gait or other movements in patients who are impaired severely by spastic hypertonia. Additionally, when stimulation of the hamstrings is used to enhance knee flexion during the swing phase of gait, clinicians should be aware of the negative effect over the hip joint.

Step length will be increased when swing limb advancement is facilitated. The step lengths found in the most affected limb of the paraplegic subjects were on average 0.55 m, whereas in healthy subjects the average step length is 0.71 m (12). In paraplegics the swing limb advancement of the legs may be decreased due to the decreased knee flexion (1). This is confirmed by our study, showing the maximal knee flexion in the paraplegic subjects (38°) was decreased compared to healthy subjects (65°) (12). The same was found for the maximum hip flexion during swing, which was 26° in these subjects, whereas the normal value is 35° (12).

The cause of the EMG signals of the subject (Fig. 1) shows an almost constant activity of three muscles in the upper leg. In healthy subjects these muscles are only active just before heel strike until mid stance (12). The EMG pattern of the paraplegic

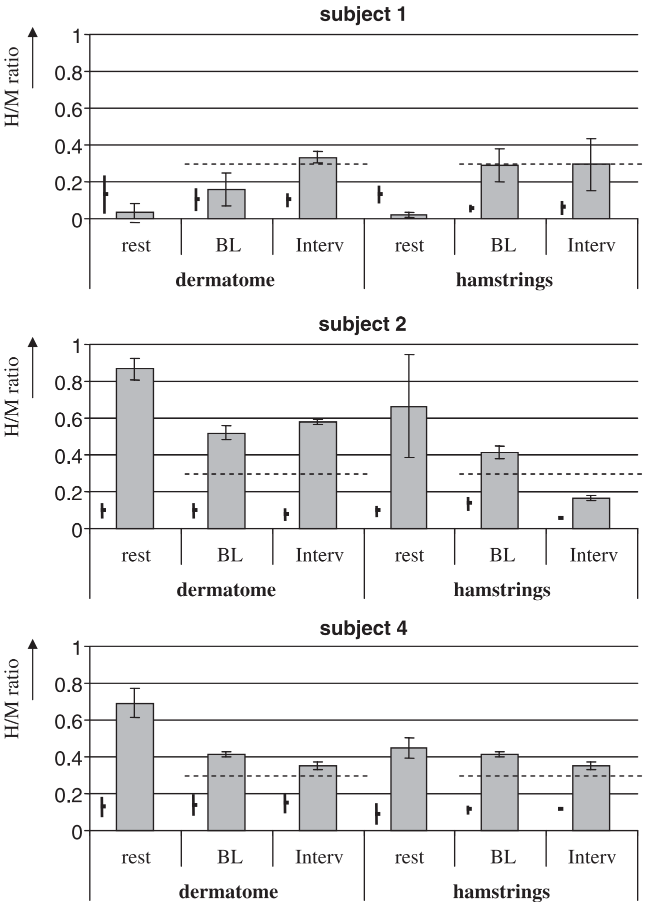

Figure 4. H/M ratio outcomes at rest and during the swing phase of gait with or without stimulation for three individual subjects. The stock graphs represent the average M/M_{max} ratios (and 1 SD), which are kept at approximately 0.1. Columns represent the H/M ratios (and 1 SD). "BL" is baseline measurement; "Interv" is the outcome of the intervention measurement. The dotted horizontal line represents the upper bound of the reference range for a group of healthy subjects.

subject indicates that the subject suffers from co-contractions due to spasticity. Individual results show that in subjects with high grades of spasticity the maximum knee flexion during swing was relatively low (Table 1). In less spastic subjects the knee flexion was larger. This indicates that more spastic subjects show a stiff-legged gait pattern.

A comparison of the individual gait parameters shows that a decreased hip flexion may affect the step length (Fig. 2; subject 2 hamstrings stimulation). This effect is less pronounced in subject 4 (Fig. 2; subject 4 hamstrings stimulation). In subject 2 there might be a relation between the changed gait performances and the increased inhibition during hamstrings stimulation.

The group results show that, despite contraction of the hamstrings due to stimulation, the knee flexion was not increased. On the other hand, the hip flexion during swing was decreased. Considering the bi-articular position of the hamstrings on the dorsal side of the hip, this might be caused by the contraction of the hamstrings. This would suggest that the effect of hamstrings stimulation is more pronounced in the hip movement than in the knee movement, which could be due to a difference in the moment arms of the hamstrings at the hip and knee. These moment arms are thought to differ during flexion or extension of the joints, whereas in upright position they are found to be equal (24). The decreased hip flexion may have decreased the swing limb advancement, reducing the step length. Stimulation of the dermatome showed no mechanical effect in any of the kinematic outcomes.

The results show that, in one out of three subjects, the H/M ratio was decreased to a normal value with hamstrings stimulation, whereas the baseline value was higher than the normal range (Fig. 3, subject 2). This indicates that the spinal reflex excitability can be normalized using ES of the antagonistic muscle. Such inhibitory effect is not found during stimulation of the dermatome. On the contrary, the H/M ratio at dermatome stimulation increases in one subject to a pathologic value, whereas the baseline value was within the normal range. In this subject dermatome stimulation has a facilitating effect in the spinal synapses. This difference in effect between the subjects might be caused by a difference in the severity of spasticity. The subject, who showed a reduction, had a relatively high grade of spasticity: MAS was 3, compared with the other two subjects, MAS was 1+ and 2 (Table 1). This indicates that, in subjects with more severe spasticity, ES may provide a higher level of inhibition in antagonist muscles. A second reason for the different change in the H/M ratio may be the difference in the time since injury. In the subject in whom hamstrings stimulation reduced the H/M ratio, the time since injury was 20 months, whereas the other subjects suffered longer from SCI: 75 and 111 months (Table 1). The spinal connections of subjects who suffer relatively long from SCI and spasticity might have adapted, which result in a change of their inhibitory pathways. This is supported by the finding that several inhibitory pathways are decreased in spastic subjects (25,26), and that there is a significant change of the reflex excitability during at least the first two years after the injury in subjects with SCI (27).

It is not expected that changes in the cycle time of one stride due to the electrical stimulation have influenced the outcome of the H/M ratio. In subject 2, in which the largest difference in the H/M ratio is found, the cycle time during hamstrings stimulation has increased by 6%. This means that the test pulse was applied at approximately 75% of the gait cycle (instead of 80%). This is still during mid swing, when no vastus lateralis activity is required (12).

Other studies found that the delay between the conditioning pulses and the test pulse (or test stretch) was important for the inhibitory effect. Fung and Barbeau (3) found that the effective delay, which provided an inhibitory effect in the soleus by stimulation of the medial plantar arch, was between 0 and 50 msec (calculated from the latest pulse). Veltink et al. (13) found the inhibitory delay between the last conditioning pulse on the peroneal nerve and a stretch of the gastrocnemius in the range of 59–184 msec. Because the stimulation location we used is different from the other studies, these delays cannot be compared directly. The effective inhibitory period of the latter study lasted for at least 125 msec. To be effective the required inhibitory period for the swing phase of gait is at least 300 msec because during this period the vastus lateralis is stretched.

The used parameters can inhibit the spinal connections, but the effect might be even more pronounced when stimulation parameters are changed. Especially at increased frequencies, more effect could be expected because more afferent action potentials will be sent to the spinal cord, which can provide an inhibitory state (3,13). The nerve fiber recruitment also might be increased using relatively high pulse widths and intensities. But, all parameters should be functional and comfortable for the subject, which is not the case at large frequencies, pulse widths, and intensities. One option may be that arrays of short bursts, as used by Veltink et al. (13), can be applied when inhibition is required. The mechanical effect with hamstrings stimulation should be kept as low as possible.

CONCLUSION

It can be concluded that hamstrings stimulation during the swing phase provides a reduction in the hip flexion in persons with SCI, whereas the knee flexion is not altered. The H/M ratio at mid swing of the vastus lateralis can be normalized using ES of the hamstrings. Stimulation of the L3/4 dermatome provides no changes in gait performance, but it can facilitate spinal connections.

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