ORIGINAL ARTICLE

Locomotor training with body weight support in SCI: EMG improvement is more optimally expressed at a low testing speed

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Study design: Case series.

Objectives: To determine the optimal testing speed at which the recovery of the EMG (electromyographic) activity should be assessed during and after body weight supported (BWS) locomotor training.

Setting: Tertiary hospital, Sint Maartenskliniek, Nijmegen, The Netherlands.

Methods: Four participants with incomplete chronic SCI were included for BWS locomotor training; one AIS-C and three AIS-D (according to the ASIA (American Spinal Injury Association) Impairment Scale or AIS). All were at least 5 years after injury. The SCI participants were trained three times a week for a period of 6 weeks. They improved their locomotor function in terms of higher walking speed, less BWS and less assistance needed. To investigate which treadmill speed for EMG assessment reflects the functional improvement most adequately, all participants were assessed weekly using the same two speeds (0.5 and 1.5 km h⁻¹, referred to as low and high speed, respectively) for 6 weeks. The change in root mean square EMG (RMS EMG) was assessed in four leg muscles; biceps femoris, rectus femoris, gastrocnemius medialis and tibialis anterior.

Results: The changes in RMS EMG occurred at similar phases of the step cycle for both walking conditions, but these changes were larger when the treadmill was set at a low speed (0.5 km h⁻¹).

Conclusion: Improvement in gait is feasible with BWS treadmill training even long after injury. The EMG changes after treadmill training are more optimally expressed using a low rather than a high testing treadmill speed.

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INTRODUCTION

Body weight supported (BWS) locomotor treadmill training became a widespread and valuable training method within the rehabilitation of patients with spinal cord injury (SCI).¹ There are two types of BWS. Initial BWS systems were based on counterweights,² while recent versions incorporate dynamic BWS, which accommodates the vertical displacement of the center of mass during gait.³ Both types have been successful in the gait rehabilitation of patients with SCI.^{2,3}

Even though functional tests (such as walking speed) are able to demonstrate changes in behavior, they do not directly reflect the motor output of the locomotor circuitry. Therefore, electromyography (EMG) is more recently used to document the progress made during training to better understand the underlying mechanisms of improvement. There are different ways to measure EMG changes during training. One can measure EMG as the performance level of the SCI person improves.⁴ This means that one measures EMG activity at higher walking speeds and lower BWS as training progresses. The disadvantage of this method is that one cannot clearly distinguish between the influence of the training effect and the changing walking speed⁵ and BWS^{6,7} on the EMG muscle activity. The other strategy

consists of performing measurements at a constant walking speed and BWS, an approach successfully pioneered by Dietz *et al.*^{8,9} As training evolved, they showed clear increases in EMG amplitude of several leg muscles during walking on a treadmill at a constant speed.

In the studies by Dietz *et al.*,^{8–10} measurements were performed at a constant treadmill speed of about 1.3–1.9 km h⁻¹. This range of walking speeds was chosen since assisted stepping movements could be most easily induced at 1.5 km h⁻¹ in complete SCI persons, and during the early part of the training in incomplete SCI persons. However, this walking speed can be rather high when compared with the speed that is preferred by the incomplete SCI patient (often around 0.5 km h⁻¹).^{11,12} In a study by Gorassini *et al.*,¹³ improvements in EMG were found in incomplete SCI persons after training as well, but the authors used a lower speed to assess the training-induced EMG changes (at their individual, pre-training preferred walking speed; averaged 1.08 km h⁻¹). The question, thus, arises whether EMG improvements are more optimally expressed when measurements are performed at higher or lower treadmill speeds. Therefore, we aimed to determine whether a low or high treadmill testing speed is more optimal to assess EMG improvements. We hypothesized that

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EMG progress should be visible at both assessment speeds, but more progress will be evident from the lower speed, as this speed is closer to the natural speed of the patient. An additional question we investigated in the current manuscript was whether patients, specifically chronic post SCI, were still able to improve after locomotor training on a treadmill with BWS, as was suggested by an earlier study.¹² This is of clinical importance since most of these patients no longer receive training.

MATERIALS AND METHODS

Participants

A convenience sample of four SCI participants (lesions obtained at least 5 years before training) participated in the locomotor training program with BWS (Table 1). The main inclusion criterion was the inability of the participant to perform unassisted locomotor movements on the treadmill when body weight was not supported. Participants were excluded if walking on the treadmill with BWS was not possible. We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research (conform to the Declaration of Helsinki).

Table 1 Patient characteristics

Participant	Age	AIS	Level of injury	Post-injury (year)	Motor-score (left/right) leg
1	50	D	T8	8	11/12
2	48	D	C4/C5	25	16/19
3	26	D	C4	6	17/15
4	53	C	T7/T8	5	20/9

Abbreviation: AIS, ASIA Impairment Scale grade.

Note that the motor-score for each leg is determined following the ASIA classification, that grades five muscle groups of each leg from L2 to S1 roots (0 = total paralysis, until 5 = active movement against full resistance).

Training program

The training program consisted of 18 sessions, given during a period of 6 weeks. Each session consisted of two times 10-min locomotor treadmill training (with a 5 min break in between). For the training, the treadmill speed and amount of BWS were adapted to the abilities of the patient. The locomotor leg movements were assisted by two trainers, each sitting at one side of the participant. The aim of the training program was to improve the SCI participants' locomotor ability, in terms of increasing walking speed together with a decrease in assistance and BWS needed. All participants increased maximum walking speed and required less BWS as training progressed (see Figure 1).

For each training session, training variables such as walking speed, amount of BWS, degree of assistance and duration of training were registered. When body weight was supported for about 40%, all four participants were able to perform stepping movements with different degrees of assistance needed from the two helpers. At the end of the training, these patients could walk with 0% BWS while the walking speed was at least doubled. During the training protocol of the current experiment, the participants received no other locomotor training in the hospital. Other physical therapy or rehabilitation protocols at home (if they received any) remained unaltered during the period of the training of the experiment.

Test protocol

To investigate the question whether functional improvement was reflected in EMG improvement, all participants were assessed weekly using the same two speeds (0.5 and 1.5 km h⁻¹, referred to as low (LTS) and high testing speed (HTS), respectively) for 6 weeks. The EMG of four muscles (biceps femoris (BF), rectus femoris (RF), gastrocnemius medialis (GM) and tibialis anterior) was measured bilaterally using surface electrodes. For both LTS and HTS, the amount of BWS was set at 20% of the participants' body weight. For the testing, a BWS of 20% was taken as this represents a good intermediate between expected starting (40% BWS¹²) and final level (0% BWS) for this type of patients. Hence, notice that for the training, the speed was adjusted; but for the testing of the EMG changes, the walking speed and BWS were kept constant during the measurements, irrespective of the improvements that were obtained

Figure 1 The development of maximal walking speed and degree of body weight support (BWS) over the training period for each participant. All participants increased maximum walking speed (—) and required less body weight support (BWS; Δ) as the training progressed.

when training progressed. For each condition, at least 15-step cycles were recorded. Foot contacts were detected using foot switches.

EMG data analysis

In Figure 2, the EMG data analysis used is illustrated based on data from a single subject.

After rectifying the band-passed EMG signals (10–500 Hz), the mean EMG profiles over the different step cycles of the different muscles were calculated for each speed condition for each week of the training (Figure 2a). The data were normalized on the basis of the foot switch data. The 'on' and 'off' state of foot contact switches served as reference points to normalize the individual stance and swing phase of each step cycle to a relative time scale. The number of data points within each step cycle was reduced to 100 by making use of the cubic spline interpolation method. Stance phase occupied 60%, and swing phase 40% of the step cycle.

An algorithm was used to calculate the time window within which the main changes in the EMG profile occurred following training. This was done by calculating the s.d. of the mean EMG profiles of each point of the step cycle as measured for the consecutive weeks. A time window was set when the s.d. was larger than the mean s.d. over the whole step cycle (Figure 2b). As we wanted to compare LTS and HTS, it was important that the windows were set for both test speeds, and that they occurred at the same percentage of the gait cycle. Within these time windows, the root mean square (RMS) of the original

rectified EMG profiles of the different step cycles for each week of training were determined (Figure 2c). To obtain the main effect of training on the RMS EMG and to smooth out any abrupt changes, the results of the first three measurements (first 2 weeks of training) were compared with the results of the last four weeks of training (Figure 2d). This allowed examination of whether changes in EMG occurred as a result of the training with BWS.

To investigate the difference between assessing EMG at a low or a high speed, the RMS EMG value of training period a (first three measurements; early training) was subtracted from that of training period b (last 4 weeks of training; late training), and were compared between speed conditions.

Statistical analysis

A one-way analysis of variance was used to test the statistical significance of the mean RMS EMG values between the two training periods. The same approach was taken for the subtracted RMS EMG values (late training minus early training) to test the difference between the two testing speed conditions. The level of significance was set at $P < 0.05$.

RESULTS

Windows settings of the EMG profiles

First we determined the window settings within which the main changes in the EMG profile occurred following training (Table 2).

Figure 2 (a) Assessment of the changes in EMG profile of the left rectus femoris (RF) over the consecutive weeks of training when assistance was minimized (0.5 km h^{-1} and 20% BWS) in participant 1. (b) Detail of how the time windows were determined within which the main changes in the EMG profile following training took place. The curve in the graph represents the s.d. of the mean EMG for all the weeks of the training at each point of the step cycle. A time window was created whenever this curve was higher than the mean s.d. over the whole step cycle (horizontal line in the graph). In this example two windows have been set, which have been indicated in a as well. (c) The mean RMS EMG values of the RF within each of the two time windows were calculated for each week. (d) To examine the effect of the training program on the EMG activity, the averaged RMS EMG values of the first three measurements (start, week 1 and week 2; white bar, period a) are compared to the averaged results of the last four measurements (week 3, week 4, week 5 and end; gray bar, period b). For this participant, the mean RMS EMG value of the RF was statistically significantly higher after training (period b) than before training (period a) for both time windows (as indicated with an asterisk). BWS, body weight support; EMG, electromyography; RMS, root mean square.

The important feature to observe is that the window settings for the two speeds of testing were very comparable. This means that changes in RMS EMG during the training program took place at similar phases of the step cycle for both LTS and HTS (that is, they can be compared with each other).

Evolution of RMS EMG values after training

The comparison of the mean RMS EMG values of each muscle was made between the beginning and end of the training (training period a compared with training period b; Figure 3).

Table 2 Time settings for the windows where the training-related changes in EMG occurred

No	Condition	BF		RF		GM		TA	
		Left	Right	Left	Right	Left	Right	Left	Right
Stance phase									
1	LTS	2–24	6–36	14–32	18–46	8–40	2–42		
	HTS	2–26	2–36	16–34	(18–46)	8–46	2–44		
2	LTS	2–46	2–42	14–40	18–46	6–38	8–36		
	HTS	2–40	2–44	10–42	18–46	8–42	8–40		
3	LTS	2–40	4–38	6–32	4–36	6–30	2–34		
	HTS	2–36	4–38	2–32	6–38	8–35	2–36		
4	LTS	2–25	8–36			4–46			
	HTS	(2–25)	6–38			6–42			
Swing phase									
1	LTS	82–100	86–100	56–70				56–92	54–100
	HTS	(82–100)	(86–100)	58–72				60–94	58–100
2	LTS							66–92	66–94
	HTS							68–92	70–92
3	LTS		86–100	62–80	58–75			62–100	66–88
	HTS		86–100	60–82	(58–75)			64–100	(66–88)
4	LTS	86–100	80–100						
	HTS	84–100	84–100						

Abbreviations: BF, biceps femoris; EMG, electromyography; GM, gastrocnemius medialis; HTS, high speed walking (at 1.5 km h⁻¹ with 20% of body weight support); LTS, low speed walking (at 0.5 km h⁻¹ with 20% of body weight support); RF, rectus femoris; TA, tibialis anterior.

Note that no windows have been set when the s.d. of the mean EMG value over the training period of each point of the step cycle was not larger than the mean s.d. over the whole step cycle, that is, when no changes in EMG were noticed (empty cells). Equivalent time settings (between brackets) have been determined when no time window was set at a similar time interval of the step cycle for both conditions.

Figure 3 The normalized mean RMS EMG value ($\pm$ s.d.) of the biceps femoris (BF) and rectus femoris (RF) in the left and right leg as determined for the two consecutive training periods (period a: early; period b: late) of participant no.1 (same participant as for Figure 2). Data are shown separately for the two time windows used (stance and late swing). For each muscle, the statistical significance ($P < 0.05$) of the difference in the RMS EMG value between the two training periods is indicated with an asterisk (*). EMG, electromyography; RMS, root mean square.

Figure 4 The effect of different testing speeds on EMG improvement. The difference of the normalized RMS EMG values between training period a and b ($\pm$ s.e.m.) during the stance phase (upper part) and swing phase of the step cycle (lower part) for the low testing speed (LTS; white bars) and high testing speed condition (HTS; gray bars). The white and gray bars represents the subtracted RMS EMG value (training period b minus training period a) as determined for the LTS and HTS condition, respectively. Asterisk signifies the difference in RMS EMG value between the two training periods. Note that more empty graphs are present for the swing phase than for the stance phase, indicating that the changes in RMS EMG values during the swing phase were less consistent across the different muscles and participants, when compared with the stance phase. BF, biceps femoris; EMG, electromyography; GM, gastrocnemius medialis; HTS, high testing speed (at 1.5 km h^{-1} with 20% of body weight support); LTS, low testing speed (at 0.5 km h^{-1} with 20% of body weight support); RMS, root mean square; RF, rectus femoris; TA, tibialis anterior.

In this participant, it can be seen that the RMS EMG values of the BF and RF increased during the course of the training program (except for the right RF during the early swing phase). In addition, it can be seen that the training-related changes in RMS EMG value varied depending on the speed used for the testing condition (that is, LTS or HTS). In contrast to LTS, left and right BF did not change significantly during the late swing phase of the step cycle in HTS, nor did the right RF during the stance phase. Hence, overall, the LTS was superior in demonstrating the changes. Furthermore, the increase in RMS EMG value was dependent on the phase of the step cycle. For example, the RMS EMG value of the RF in the right leg changed during the stance phase, but did not change during the early swing phase of the step cycle.

Effect of different speeds used for EMG assessment

The same analysis as illustrated in Figure 3, was performed for all participants. To accentuate the difference due to the testing speeds, the subtracted RMS EMG value (late training minus early training) was plotted for the different muscles and for the two testing speed conditions (Figure 4).

Figure 4 shows that the increase in RMS EMG at late training was accentuated when using the LTS. On average, the increase was $21 \pm 6\%$ and $34 \pm 4\%$ for the HTS and LTS condition, respectively. The larger increase in RMS EMG value during LTS when compared with HTS was significantly present in participants 1, 2 and 3 ($F_{LTS/HTS}(1,21) = 13.6$, $P < 0.001$; $F_{LTS/HTS}(1,5) = 5.8$, $P < 0.05$; $F_{LTS/HTS}(1,21) = 6.5$, $P < 0.05$, respectively). In participant 4, we could not calculate the significance level since only five muscles showed changes in the RMS EMG value. Nevertheless, four out five muscles in this participant showed a larger change in the RMS EMG value during LTS than during HTS. Furthermore, the difference between LTS and HTS was most prominently present during the swing phase when compared with the stance phase. On average for HTS and LTS, the increase during the swing phase was $15 \pm 5\%$ and $35 \pm 4\%$, respectively; whereas in the stance phase, the mean increase in RMS EMG was $24 \pm 7\%$ and $34 \pm 4\%$ for the HTS and LTS conditions, respectively.

DISCUSSION

In the current study, we confirmed that locomotor abilities can be improved after treadmill training with BWS in chronic SCI participants.^{9,12,13} Furthermore, it was shown that an objective EMG assessment is best performed using a low testing speed.

Concerning the first result, the improvement is clinically highly relevant, as these chronic patients usually do not receive gait rehabilitation. The changes in RMS EMG of BF, RF and GM took place during the first part of the stance phase. The main action during this phase is body weight acceptance and body weight bearing on the leg.¹⁴ Since during gait the GM is an important antigravity muscle, the increase of RMS EMG of the GM during the stance phase can be considered as functionally useful. In addition, since BF and RF are part of the hamstrings and quadriceps, respectively, the increased RMS EMG of BF and RF during the early part of the stance phase may have yielded a more stabilized knee joint. Furthermore, the changes in RMS EMG of the BF, RF and GM during the first part of the stance phase likely improved the antigravity function of the loaded leg. This is an important finding in the context of the theoretical background of treadmill training,^{15–17} which states that afferent inputs, which have direct access to the central pattern generator, can re-establish basic locomotor rhythmicity. It is thought that the load-related input inhibits the

premotor center for the generation of flexion during the stance phase, thereby exciting the motoneurons of extensor muscles.^{16,17} For example, Dietz *et al.*^{8,9} showed that the EMG amplitude of the GM increased during the stance phase of the step cycle following locomotor training with BWS, when training was started shortly after injury. Similar to these results, it was presently found that GM EMG activity also increased in SCI persons when trained long after injury. These results show that the onset of training after injury is not always the primary requirement to enhance GM EMG activity during the stance phase.

A second major result concerns the superiority of LTS over HTS. On average, the increase of the RMS EMG value with the LTS was about 10% larger than the one found with the HTS. It is proposed that the reason that the LTS is a more optimal testing condition, is because it is closer to the participants' normal speed. In contrast, during the HTS, the applied treadmill speed was higher than the walking speed that was obtained by the SCI at the end of training. Therefore, the conditions during LTS were within the capabilities of the SCI participant during the whole training program, whereas this was not the case for HTS. The fact that large changes were still observed even in suboptimal testing conditions underlines the robustness of the improvements obtained with treadmill training.⁹ Nevertheless, it is important to realize that electromyographic progress in walking ability is more optimally expressed when testing occurs at a low rather than at high treadmill speed.

DATA ARCHIVING

There were no data to deposit.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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