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FUNCTIONAL ELECTRICAL STIMULATION-ASSISTED WALKING FOR PERSONS WITH INCOMPLETE SPINAL INJURIES: CHANGES IN THE KINEMATICS AND PHYSIOLOGICAL COST OF OVERGROUND WALKING

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This study was conducted to investigate the change in the kinematics and physiological cost of walking that occurs during training with functional electrical stimulation (FES)-assisted walking in persons with incomplete injuries. The main effect of FES-assisted walking was to change hip excursion and ankle dorsiflexion during swing and at foot contact, whereas training with FES-assisted walking changed the spatio-temporal parameters of walking (walking speed, cycle length and frequency as well as time in stance). The use of FES-assisted walking does not change the walking speed achieved during a 5-minute trial nor the physiological cost of walking but when combined with walking training, eight of the nine participants improved either their physiological cost index or their walking speed. It is concluded that FES-assisted walking changes the joint angular kinematic pattern of walking, but training is necessary to integrate these changes into functional gains.

Key words: rehabilitation, electric stimulation therapy, paraplegia, gait, locomotion, kinematics.

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INTRODUCTION

Increases in functional mobility for 12 out of 14 persons with spinal cord-injuries with incomplete motor function loss (SCI-IMFL) were shown in a previous study involving long-term use of functional electrical stimulation (FES)-assisted walking (6). This increase was partly due to a change in the type of ambulatory assistive devices as well as time-dependent increase in the maximal overground walking speed whether the participant was using FES-assisted walking or not. The increase in walking speed with FES-assisted walking was negatively correlated with initial walking speed, and no difference was found between FES-assisted and non-assisted walking. Furthermore, changes were not instantaneous but were dependent on the time of start of FES-assisted walking.

Changes in walking speed, stride length and stride frequency with the use of FES-assisted walking have been reported for SCI-IMFL for electrically activated common peroneal (1, 9) and tibial nerves (2). Stein and collaborators reported an improvement of 0.08 m/second when using FES-assisted walking independently from their control walking speed (9). This improvement was not linked to changes in either stride length or frequency. Another study measuring the therapeutic effect of FES-assisted walking by SCI-IMFL showed no difference in walking speed or stride frequency but an increased stride length (5). This study also reported that three out of six participants increased their walking speed (5). This increase in walking speed could be explained by changes in stride length, stride frequency, or a combination of both factors (5). With the exception of one study using tibial nerve stimulation (2), joint angular kinematics was reported only as examples (9). No studies have reported kinematic changes occurring with the use of FES-assisted walking or have evaluated the changes during a long-term walking programme using FES-assisted walking.

Another factor in the evaluation of the functional and rehabilitation benefits of using FES-assisted walking is the energy requirement necessary for ambulation. Although wheelchair propulsion approximates the energy requirement of normal walking (3), the energy cost of walking by SCI-IMFL is higher than for speed-matched walking by able-bodied participants (9). When using FES-assisted walking, SCI-IMFL does not reduce participants' oxygen consumption (9), although a reduction in the physiological cost index (8) has been shown after 12 weeks of training (5).

The purpose of this study is twofold. First, changes in the kinematics of the lower limb are examined when the participant is using FES-assisted walking over a long period of training. Second, the purpose of this study is to report the changes in walking speed and the physiological cost of walking during a 5-minute walk when the participant is using FES-assisted walking over a long period of training.

METHODS

Fourteen SCI-IMFL persons participated in this study. All participants were also involved in a study of the changes in maximal overground walking speed with the use of FES-assisted walking (6). Relevant characteristics of the participants can be found in Table I.

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Table I. *Characteristics of the participants (n = 14)*

Participants	Neurological level of lesion	IMSOP	Time post injury (years)	Age (years)	Mob.Score (Init.)	AAD (Init)	AAD (<1 year)	FES orthosis				Outcome variables analysed			Time for the <1 year condition (weeks)
								Qr	Ql	Pr	Pl	Energy cost	Joint angular	Spatio-temporal	
AC	T12-L1	P_D	12.3	34.0	80	1C	1C			✠	✠	✠	✠	✠	50
DB	T8	P_D	6.6	36.0	74	2K	2K			✠	✠	✠	✠	✠	45
DT	T11	P_C	3.1	31.8	45	W	W			✠	✠	✠			
FG	C5-C6	T_D	3.7	48.9	62	2C	2C			✠	✠	✠	✠	✠	44
JB	T10	P_D	2.5	37.8	78	1C	1C			✠		✠	✠	✠	49
LR	T10	P_D	19.1	32.4	63	2K	2K			✠	✠	✠			
LS	T9-T12	P_C	9.9	36.3	60	W	2K	✠	✠	✠	✠			✠	29
MA	C5-C6	T_C	6.1	36.3	54	W	2K			✠	✠	✠		✠	26
MR	C3-C6	T_D	6.3	26.8	83	1C	1C				✠'	✠	✠	✠	26
MS	C6	T_D	8.8	27.6	73	2K	2K			✠	✠	✠			
RL	C5	T_D	1.8	29.1	59	2K	2K			✠					
RP	C5-C6	T_C	4.3	28.5	58	W	2K	✠	✠	✠	✠	✠	✠	✠	46
SH	C7	P_C	6.1	30.8	64	W	W			✠	✠	✠	✠	✠	56
SM	C5-C6	T_D	4.3	25.0	66	W	2K				✠	✠	✠	✠	43

IMSOP = International Medical Society of Paraplegia; AAD = ambulatory assistive device; C = cane; K = forearm crutches; W = walker; Qr–Ql = stimulation of the right and left quadriceps; Pr–Pl = stimulation of the right and left common peroneal nerve; ✠' = stimulation of the tibial nerve.

Kinematics

The kinematic patterns in the sagittal plane and temporal variables were reconstructed from video recordings of the most affected side. The data were digitized and reconstructed using a Peak Performance Analysis system. Markers were placed on the lateral side of the 5th metatarsal, heel, lateral malleolus, knee joint axis, greater trocanter and acromion. The participants were asked to walk at their comfortable walking speed on a 5-m walkway. The video recordings were digitized and joint angle time-courses were calculated. The measurements followed the International Society of Biomechanics convention (11). The stride duration and stride length were extracted for each cycle from the heel marker trajectory. Hip, knee and ankle excursions were measured from the peak-to-peak values for each cycle from the joint angular excursions. Ankle angles at foot contact and during mid-swing were also extracted for each cycle from the ankle joint angular excursion. The results were compared using an analysis of variance for each parameter (repeated measure 2×2; stimulation $\times$ time; Systat, V5.0).

Physiological cost of walking

The physiological cost of walking, was measured with the physiological cost index. The index was established by dividing the difference between the heart rate during walking and during sitting with the walking speed measured in metres per minute. The result of this calculation is the physiological cost of walking in heart beats per metre walked. The recordings were made by asking the participants to sit for a period of 5 minutes, to stand for a period of 3 minutes and then to walk for a period of at least 5 minutes on a 15-m walkway. After the completion of the walking period, the participants were asked to sit again and to rest until their heart rate was back to the resting value found during sitting. Once the heart rate reached this level, the procedure was repeated. The use of FES-assisted walking was randomized. When possible, the participants were asked to repeat the procedures with the different ambulatory assistive devices they were able to use. Heart rate was recorded by a Polar Vantage XL heart rate monitor (Polar Electro Oy, Finland; see (7) for validity and stability). The values for sitting heart rate, walking heart rate, and walking speed represent the average of the last 30 seconds of recordings for the appropriate condition. Walking speed was calculated from times recorded by a manual stopwatch at each end of the 15-m walkway. A paired *t*-test was used to assess the effect of FES-assisted walking on walking speed and physiological cost of walking measures.

RESULTS

Kinematics

Spatio-temporal parameters. We analysed the spatio-temporal changes by using FES-assisted walking in 10 participants (Table I). The remaining four participants were not analysed because the initial data with the use of FES-assisted walking were not collected or some of the participants stopped using this technique before a final kinematic evaluation could be performed.

Fig. 1 shows examples of the changes in the spatio-temporal parameters found with a programme of FES-assisted walking (Figs. 1A–1C; one stride in each condition). A comparison of Figs. 1A and 1B shows the increased stride length (0.61 and 1.22 m) and reduced stride time (4.4 and 3.9 seconds) that occurred with long-term use (43 weeks) of FES-assisted walking even though the stimulator was turned off both times. The example also shows that using FES-assisted walking has a minor effect on stride length (1.22 to 1.28 m) and stride time (3.9 to 3.2 seconds for this example, although the average in both conditions is 3.6 seconds) when the comparison is made for the same day (Figs. 1C versus 1B).

As shown in Fig. 2, training with FES-assisted walking during

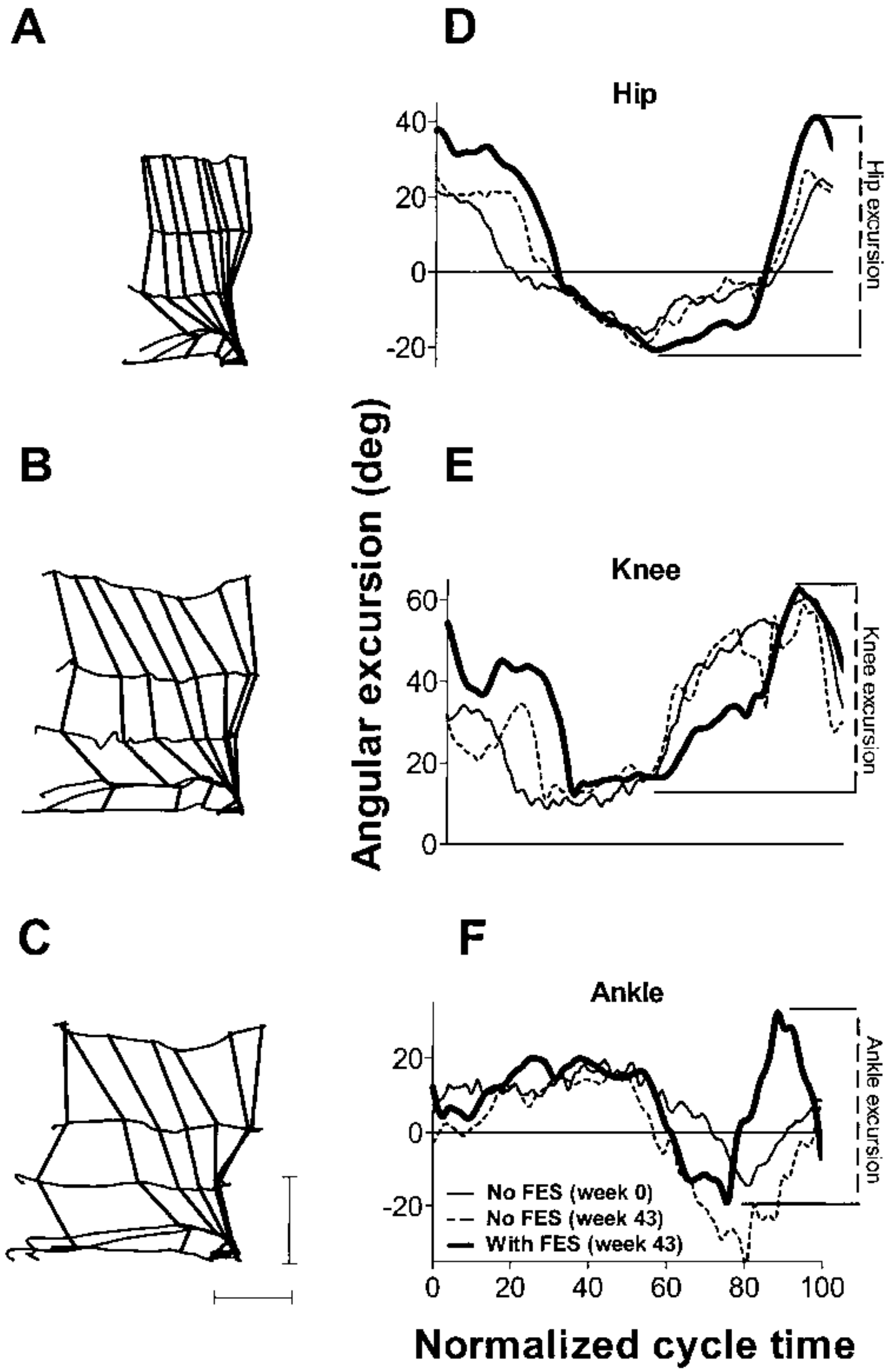

Fig. 1. Example of the changes in the kinematics with FES-assisted walking. Panels A–C show the stick figure (every 0.5 seconds) and trajectories of retro-reflective markers (see Methods) when SM walks without FES at the beginning of FES-assisted walking (A), without FES but after 43 weeks of FES-assisted walking (B) and with the FES-assisted walking at the same evaluation session (C). Panels D–F show the angular excursion of the hip (D), knee (E) and ankle (F) of the affected lower limb in these trials. Calibration bars for panels A–C represent 0.5 m. The hip, knee and ankle angular excursions (D–F) without FES-assisted walking at onset of training, without FES-assisted walking after 43 weeks of training, and with FES-assisted walking after 43 weeks of training are represented by thin, dotted and thick lines, respectively.

the first year increased walking speed by 0.10 m/second (Table II and Fig. 2A). This improvement in walking speed results from an average increase of 0.12 m in stride length and 0.04 Hz in stride frequency (Table II and Figs. 2B and 2C, respectively). The increase in stride frequency is due to a decreased stance time of 0.22 seconds with only minor changes in the swing duration (Table II and Fig. 2D). Surprisingly, FES-assisted walking had only minor effects on any of the spatio-temporal parameters investigated in this study (Table II).

Longitudinal changes in the spatio-temporal parameters of one representative participant are shown in Fig. 3 (SM; Figs. 3E–F). It can be seen in this figure that changes in the spatio-

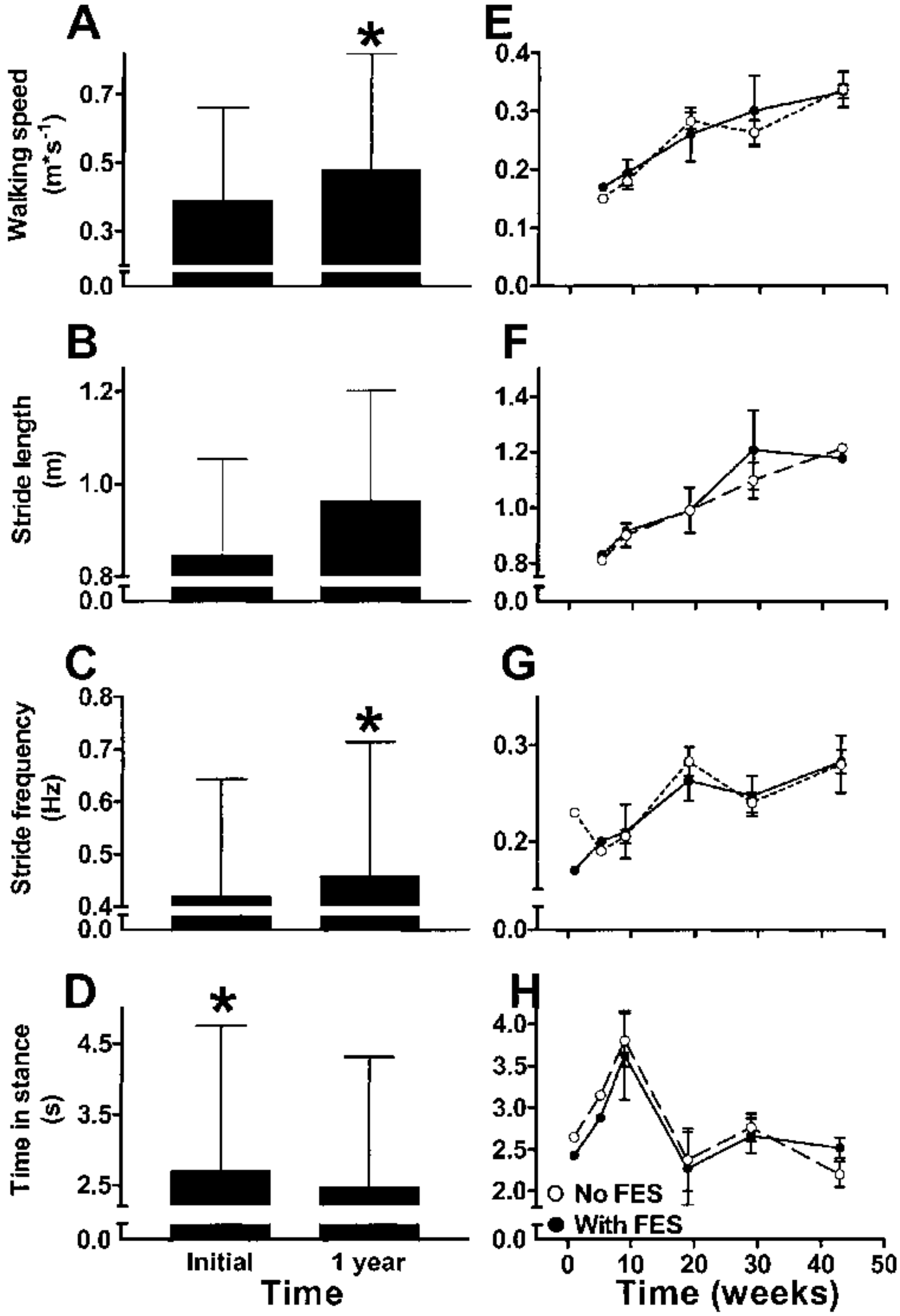

Fig. 2. Changes in the spatio-temporal parameters with FES-assisted walking. Panels A–D show the significant changes occurring during the first year for walking speed (A), stride length (B), stride frequency (C), and time in stance (D). Examples of longitudinal changes in the walking speed (E), stride length (F), stride frequency (G), and time in stance (H) for one participant (SM) are also presented. Panels B, C, F and G show that both stride length and frequency are changed when there is a modification of the walking speed. Panels C, D, G and H show that modification in the cycle time is related to modification of the stance time. Significant differences in the means are indicated with an asterisk, whereas the non-assisted and FES-assisted walking conditions are represented, respectively, by open and filled circles.

temporal parameters are not instantaneous but are dependent on duration of the FES-assisted walking programme.

Joint angular parameters

Joint angular measurements were extracted for eight participants (Table I) but hip angular excursion was the only measurement extracted for one participant (LS). Figure 1 illustrates examples of the changes occurring with the use of FES-assisted walking as well as changes occurring with the training programme (Figs. 1D–F). One stride is shown for each condition. Hip angular excursion increases with FES-assisted walking but changes only minimally with time (Fig. 1D). Figure 1E shows the time-normalized angular joint excursion of the knee. It can be seen that the angular excursion does not change with and without FES-assisted walking nor with time. However, the angular pattern is modified with FES-assisted walking, the knee being

Table II. *Statistical results of selected outcome variables*

	Initial- <1 year		No.—with FES	
	Result	*p*-value	Result	*p*-value
Spatio-temporal variables				
Walking speed	$F_{(1,9)} = 11.90$	0.007	$F_{(1,9)} = 0.00$	0.991
Stride length	$F_{(1,9)} = 4.43$	0.065	$F_{(1,9)} = 0.12$	0.737
Stride frequency	$F_{(1,9)} = 13.26$	0.005	$F_{(1,9)} = 0.40$	0.541
Stance duration	$F_{(1,9)} = 9.43$	0.013	$F_{(1,9)} = 0.24$	0.235
Swing duration	$F_{(1,9)} = 2.82$	0.127	$F_{(1,9)} = 3.22$	0.106
Joint angular parameters				
Hip angular excursion	$F_{(1,8)} = 1.68$	0.231	$F_{(1,7)} = 6.65$	0.033
Knee angular excursion	$F_{(1,7)} = 0.26$	0.625	$F_{(1,7)} = 0.73$	0.421
Ankle angular excursion	$F_{(1,7)} = 0.02$	0.883	$F_{(1,7)} = 0.94$	0.364
Ankle angle at foot contact	$F_{(1,7)} = 2.08$	0.193	$F_{(1,7)} = 8.54$	0.022
Ankle dorsiflexion angle during swing	$F_{(1,7)} = 0.31$	0.597	$F_{(1,7)} = 19.37$	0.003
Energy cost				
Walking speed			$t_{(11)} = 0.63$	0.543
PCI			$t_{(11)} = 1.18$	0.264

F = results from an ANOVA; *t* = results from Student's *t*-test; *p* = probability of type I errors.

more flexed in the early stance phase and more extended in the later stance phase (from 0 to 30% and 50 to 80% of the normalized cycle time, respectively). Figure 1F represents the time-normalized angular excursion of the ankle. Although the ankle angular excursion during the stride does not change among the three conditions, there was an increased ankle dorsiflexion angle during the swing phase of gait when FES-assisted walking was used. The use of FES-assisted walking increased hip angular excursion by 3.2° (Table II and Fig. 3A). In addition, it increased ankle dorsiflexion during the swing phase by 10.9° and decreased ankle plantar/flexion at foot contact by 5.6° (Table II and Figs. 3B–C). In contrast, the knee and ankle angular excursions did not change (Table II). There were small changes in the joint angular parameters with the duration of the FES-assisted walking training programme (Table II).

Longitudinal changes in selected joint angular parameters of one representative participant are shown in Fig. 3 (SM; Figs. 3D–F). Unlike the longitudinal changes reported for the spatio-temporal parameters in Fig. 2, there is no clear increase in the joint angular parameters associated with the duration of the FES-assisted walking training programme. However in most of the evaluations there was a greater hip angle excursion, ankle angle at foot contact, and ankle dorsiflexion during swing with FES-assisted walking compared with the control condition (Figs. 3D–F, respectively).

Physiological cost of walking

The effect of FES-assisted walking on the physiological cost index and walking speed during the 5-minute walk was examined in 12 participants who had been using the programme for at least three months (Table I). Because initial measurement of the physiological cost of walking, as measured by the physiological cost index, was not acquired at the onset of FES-assisted walking for four participants the effect of time was not investigated. An example of the data recorded by the heart rate monitor can be found in Fig. 4A. The heart rate increased for participant RP from about 110 beats per minute when he was sitting to about 160 beats per minute when he was walking. Although, the changes in the heart rate remained constant, his walking speed doubled with the use of FES-assisted walking, which diminished the physiological cost of walking by a factor of two. As seen in Fig. 4B, FES-assisted walking did not have any effect on either the physiological cost index or the walking speed during the 5-minute walk (Table II). Changes in walking speed during the 5-minute walk with FES-assisted walking were correlated to the walking speed in the control condition ($r = -0.571$; $p = 0.052$) but not the physiological cost index ($r = 0.419$; $p = 0.175$).

This study shows that the use of FES-assisted walking does not change the walking speed or the physiological cost of walking. To evaluate the effect of training with FES-assisted walking on the physiological cost of walking we studied 9 participants longitudinally from onset of FES-assisted walking. When combined with time, we see five different types of responses: in three participants the physiological cost index remained constant and the walking speed increased, in three participants the physiological cost index decreased and the walking speed remained constant, in one participant the physiological cost index decreased and the walking speed increased (DT; Fig. 4C), in one participant the physiological cost index and walking speed increased, and in one participant the physiological cost index increased and the walking speed remained constant. These results show a positive effect for 8 out of the 9 participants who were evaluated for a duration of more then 3 months.

DISCUSSION

The aim of this study was to characterize the magnitude and time-course of changes in kinematic and physiological cost parameters of walking FES-assisted walking for SCI-IMFL. The main results are that spatio-temporal parameters of walking are

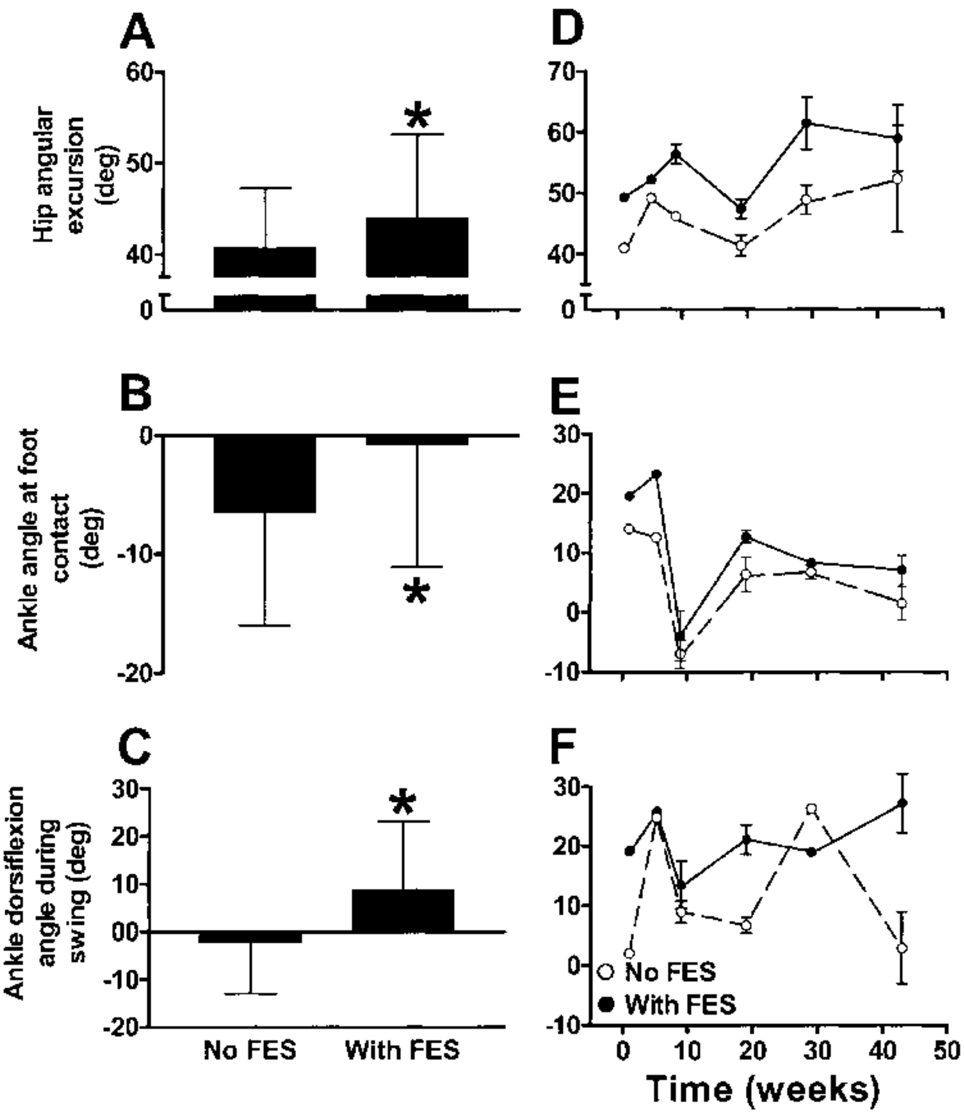

Fig. 3. Changes in the angular parameters with FES-assisted walking. Panels A–C show the significant changes that occur with FES-assisted walking for hip angular excursion (A), ankle angle at foot contact (B), and ankle dorsiflexion angle during swing (C). Examples of longitudinal changes in hip angular excursion (D), ankle angle at foot contact (E), and ankle dorsiflexion angle during swing (F) for one participant (SM) are also presented. Panel D through F show that hip angular excursion, ankle angle at foot contact and ankle dorsiflexion angle during swing remain constant with long-term use of FES-assisted walking but differ between walking with and without FES assistance. Positive angular values represented in panels B, C, E and F represent dorsiflexion, whereas negative values represent plantar/flexion. Significant differences in the means are represented with an asterisk, whereas the non-assisted and FES-assisted walking conditions are represented by open and filled circles, respectively.

similar with and without FES-assisted walking but improve with the duration of the FES-assisted training programme and that both stride length and frequency are factors in the increased walking speed with time. In contrast, joint angular parameters of walking change with the use of FES-assisted walking but change minimally with the duration of the FES-assisted walking training programme. There was no difference in the physiological cost of walking nor walking speed when the participant used FES-assisted walking. However, the majority of participants that were followed longitudinally show some positive effects.

The minor differences observed in the walking speed with and without FES-assisted walking during the kinematic and physiological cost of walking evaluations are similar to results found for maximal overground walking speed reported in a previous study (6). However, this is the first study showing that the increase in walking speed is related to an increase in both stride length and stride frequency and that changes in the stride frequency are related to changes in the duration of stance. Previous studies showed that the use of FES-assisted walking could be related to changes in both stride frequency and stride length (4, 5), but trends could not be extracted because of the limited number of participants. This study is the first to report changes in joint angular parameters with use of a peroneal nerve stimulator for SCI-IMFL. In this study, there was no difference in the physiological cost of walking during FES-assisted walking. This is similar to results found by an earlier study using oxygen consumption (9). In addition, changes in the physiological cost of walking when the participants were not using FES-assisted walking have been reported previously (5). This study showed that these changes were progressive.

It is surprising to note that the changes in walking speed reported for the kinematic evaluation during the first year of FES-assisted walking are about half that reported for maximal overground walking speed (0.10 m/second in comparison to 0.25 m/second). Since there was no interaction factor between the use

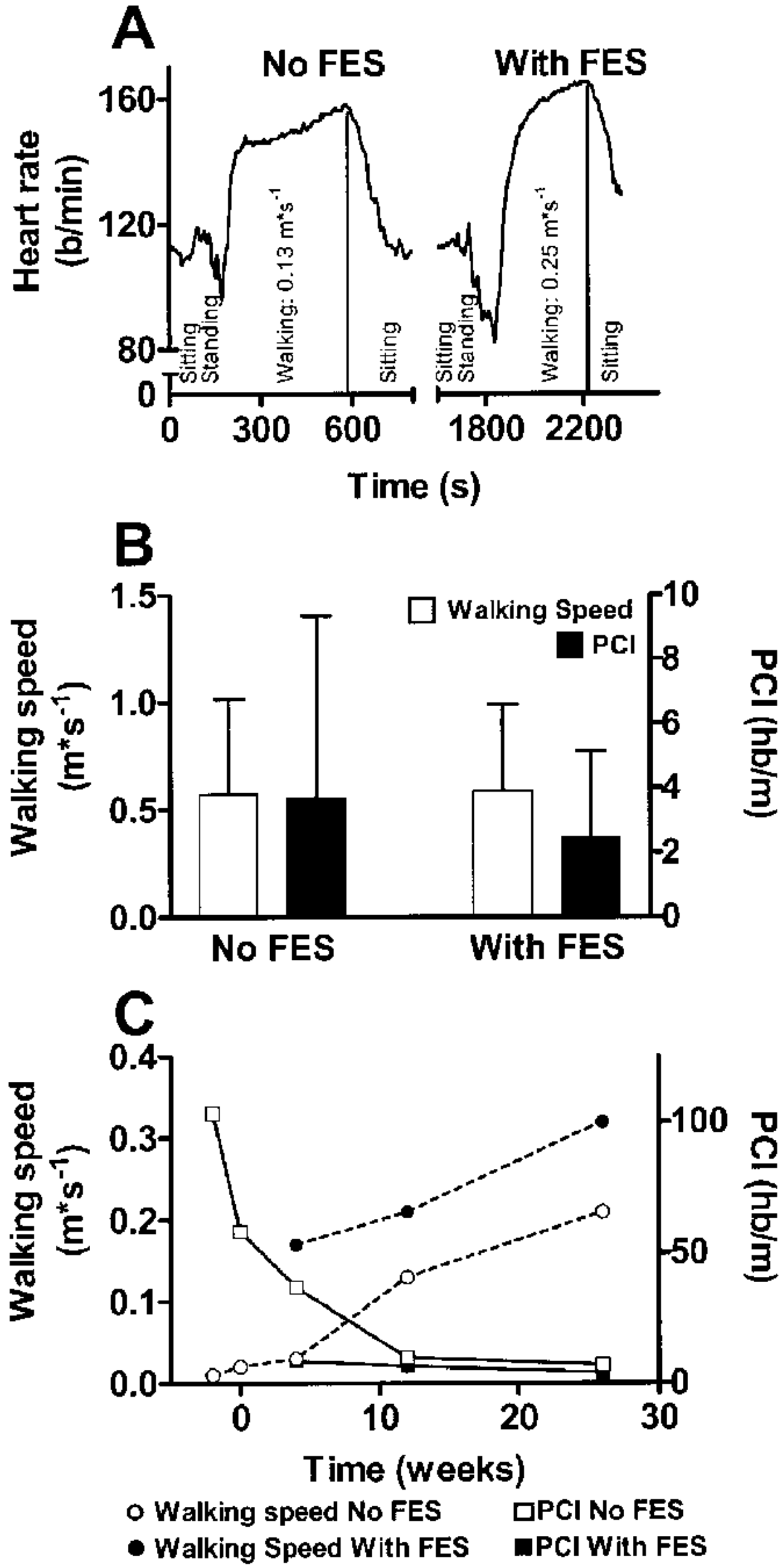

Fig. 4. Physiological cost of FES-assisted walking. Panel A shows an example of the raw data used to calculate the PCI. Panel B shows the mean and standard deviations of the walking speed (clear bar and left axis) in the therapeutic (no FES) and combined conditions (with FES) as well as for the PCI (filled bar and right axis). Panel C presents as an example of the longitudinal changes in the physiological cost of FES-assisted walking, the only participant (DT) who had a decrease in PCI combined with an increased walking speed. Significant differences in the means are represented with an asterisk. The non-assisted and FES-assisted walking conditions are represented by open and filled symbols, respectively, whereas walking speed is represented by circles and PCI by squares.

of FES-assisted walking and duration of the FES-assisted walking training programme, the improvement in walking speed is entirely due to the therapeutic effect of the training program. This result has also been showed in a previous report (6). As discussed in this study, the improvement occurs because changes can occur at many sites within the nervous and muscular systems.

Because of the heterogeneity of our sample, the results of this study have many functional implications that can be relevant to the whole spectrum of SCI-IMFL. For example, this study shows that FES-assisted walking can be used as a rehabilitation device that would enhance the recovery of walking. Furthermore, the results of this study show that even though the participants were classified as chronic SCI-IMFL patients, it is still possible to improve their walking behaviour when an appropriate treatment modality is used.

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