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ORIGINAL ARTICLE

FES assisted standing in people with incomplete spinal cord injury: a single case design series

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Study design: Single case cross-over design with multiple baselines.
Objective: To compare two functional electrical stimulation (FES) training protocols to assist sit-to-stand in people with incomplete spinal cord injury (SCI).
Setting: The study was conducted in Sydney, Australia.
Methods: Four subjects with incomplete SCI undertook nine sessions of FES supported cycling at either 100 or 35 Hz stimulus frequency repeated. Ground reaction force and rate of generation of vertical ground reaction force during standing from sitting were measured before and after each training series.
Results: Subjects improved their ability to generate greater support through the feet after training with 35 Hz stimulus paradigm but increased the rate of force production after training with 100 Hz stimulation.
Conclusions: Different FES training paradigms appear to produce different responses; however the ability to stand up seems more responsive to training with 35 Hz FES stimulation.
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Keywords: electric stimulation therapy; exercise; rehabilitation; spinal cord injuries

Functional electrical stimulation (FES) has been used for 50 years to obtain controlled contraction of paralyzed muscle,[1] particularly after spinal cord injury (SCI).[2] FES has been reported to increase muscle cross-sectional area[3] and assist functional activities.[4] As SCI leads to rapid and extensive muscle atrophy[5] with reduction in power generation capacity,[6] such therapeutic benefits may be important. Although between 65 and 70% of SCI are classified as incomplete lesions (iSCI),[7] the diversity of motor loss and sparing means that the functional prognosis for such people may be little better than for those with complete lesions.[8]

Standing and walking are typical rehabilitation priorities for people with SCI. However, to stand up from a chair requires considerable strength and power,[9] in particular from the hip and knee extensor muscles. The use of FES to assist such activities has some currency in iSCI[10] and FES-assisted cycling and resisted exercise have been shown to improve muscle strength.[3,11] Whether such training can elicit sufficient muscle strength and power to restore sit-to-stand ability in people with iSCI has not been reported.

Most studies using FES in this manner employ a stimulation frequency of 35 Hz.[12] However, a number of studies have suggested that an enhanced effect on muscle contraction may be obtained through the use of electrical stimuli at higher frequencies up to 100 Hz,[13–15] which produce synaptic recruitment of spinal motoneurons[16] and recruit a greater number of fatigue resistant motor units through reflex activation of smaller motoneurons,[17] but there have been no reported studies in which training using stimulation frequencies of 35 and 100 Hz have been compared in terms of their benefits to functional activity such as standing from sitting.

This exploratory investigation involved a repeated series of single case studies using a cross-over design with a randomized order of training to compare 100 Hz, high frequency (HF) and 35 Hz, standard frequency (SF) stimulation protocols and their effects on recovery of standing up.

MATERIALS AND METHODS

Participants

Participants were recruited from among community-living people with iSCI in Sydney, Australia. Inclusion criteria were: (i) having sustained a SCI at least 1 year before the commencement of the study resulting in incomplete paralysis (classification ASIA C or D); (ii) being aged between 18 and 65; (iii) having no other medical problems likely to influence test performance (for example, old fractures, contractures, newly formed decubitus ulcers); and (iv) being able to tolerate levels of FES sufficient to produce knee extension.

Body mass, height, gender and age were recorded as was the manual muscle test scores for the knee and hip extensors (Table 1). All participants gave written informed consent to the testing procedures and data were de-identified and coded. Institutional approval was granted for this study (ref no.: 04-2008/10769).

Test protocol

A custom-designed transcutaneous neuromuscular stimulator[18] generating square wave, monophasic pulses of width 300 μs, at frequencies of either 35 Hz (SF) or 100 Hz (HF) was employed. Monophasic pulse was used because

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Table 1 Subject characteristics

Subject	Gender	Age (years)	Height (cm)	Mass (kg)	SCI level	ASIA impairment scale (AIS)	Time since injury (months)	Manual Muscle Test (Oxford Scale)			
								Right knee extensors	Right hip extensors	Left knee extensors	Left hip extensors
A	M	59	168	85	T8	C	276	3	2	1	2
B	M	53	178	77	T8	C	72	3	2	3	2
C	F	22	145	43	T10	C	72	3	2	2	2
D	M	41	180	165	C6	C	21	3	2	2	1

Table 2 Stimulation intensities (mA) used to assist standing up during tests

Subject	Pre-training								Post-training 1								Post-training 2							
	SF				HF				SF				HF				SF				HF			
	RKE	LKE	RHE	LHE	RKE	LKE	RHE	LHE	RKE	LKE	RHE	LHE	RKE	LKE	RHE	LHE	RKE	LKE	RHE	LHE	RKE	LKE	RHE	LHE
A	90	60	60	70	70	50	60	45	86	57	61	68	71	42	56	46	85	65	70	67	80	63	66	63
B	60	50	75	80	60	55	80	70	60	55	75	75	60	58	75	73	60	55	68	68	60	60	65	65
C	25	40	70	88	27	35	70	90	27	35	70	85	30	33	73	83	25	31	74	77	28	27	75	80
D	115	113	100	91	100	105	99	98	120	118	98	95	108	102	107	99	120	118	98	95	116	110	110	103

Abbreviations: HF, 100 Hz stimulation frequency; LHE, left hip extensors; LKE, left knee extensors; RHE, right hip extensors; RKE, right knee extensors; SF, 35 Hz stimulation frequency.

the stimulator did not have the capacity to deliver 100 Hz stimulation with biphasic pulses. Skin-surface, self-adhesive electrodes (13 × 5 cm; StimCare Carbon FM Electrodes, Medi-Stim Inc., Wabasha, MN, USA) were placed bilaterally over the proximal antero-lateral and distal antero-medial surfaces of the quadriceps femoris muscle and over the proximal and distal ends of the gluteus maximus muscle. Stimulation amplitudes were set according to individual tolerance and requirement to achieve knee and hip extension. This amplitude was determined through a number of practices before each test session. Details of stimulation intensities are included in Table 2.

Subjects sat in a chair with each foot on a force platform (AMTI, Watertown, MA, USA) and with a set of parallel bars positioned such that they could use these for balance or to assist them to stand if required. On a verbal cue, subjects were told to attempt to stand up and stimulation was applied to the knee and hip extensors. A total of five trials were performed, with a rest period of 2 min between each trial. SF and HF tests were conducted on different days, at the same time of day. Subjects were protected, but not supported, by a harness attached to an overhead beam throughout the test.

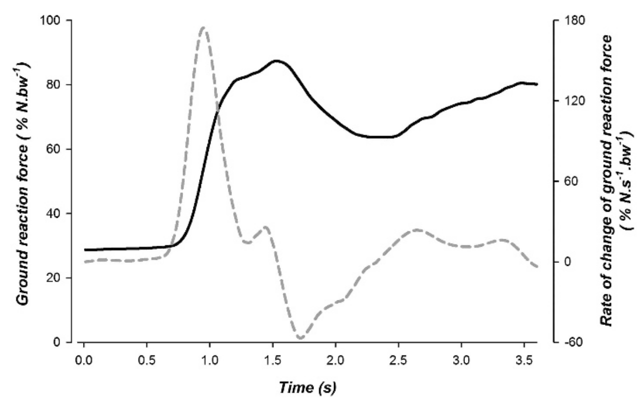

Figure 1 Typical ground reaction force pattern and rate of change of force during sit-to-stand. Solid line = vertical grf (F_{gr}). Dashed line = $\delta F_{gr}/\delta t$ (scale on right vertical axis).

Training protocol

Before training, all subjects were tested using the above protocol. Subjects were randomly assigned to receive training using either HF or SF stimulation for three sessions per week for 3 weeks. This was followed by a repeat of the test protocol and a cross-over in which they received the alternative stimulation protocol for the same training for a further nine sessions, after which they were again tested.

Each subject participated in FES-supported, semi-recumbent cycling using a motorized cycle ergometer and a muscle stimulator.[18] The quadriceps, hamstrings and glutei were stimulated via monophasic, rectangular pulses with a pulse width of 300 μs over preset angles during the pedaling cycle, which was conducted at a cadence of 50 r.p.m. Consistency of muscle fiber recruitment was ensured through the use of key anatomical landmarks to ensure similar electrode placement. The maximum stimulation amplitude was manually incremented as muscles fatigued and was limited to 140 mA. Each training session lasted 45 min. Subjects also underwent a training program consisting of three sets of eight repetition maximum resistance weights applied to the knee and hip extensors with FES support. Adequate rest periods were given to allow recovery between exercise sessions.

Data capture and analysis

The ground reaction force (F_{gr}) under the subject's feet was collected in real-time at 100 Hz. This gives a measure of the extent to which the subject was able to achieve independent standing. The difference between the value of F_{gr} and the subject's body weight is a proxy for the amount of force transmitted through the hands. Maximum F_{gr} was calculated for each trial at each test session.

Because power is necessary to achieve standing[9] and this is a function of the rate at which force can be generated, the instantaneous first derivative of F_{gr} ($\delta F_{gr}/\delta t$) was calculated and the peak value during the rise to stand recorded (Figure 1).

In light of the single case design of the investigation, no inferential statistical analysis was conducted. Determination of the stability of observations was established through reporting of the coefficient of variance for the five trials at each test session for maximum F_{gr} and maximum $\delta F_{gr}/\delta t$.

RESULTS

Four suitable subjects were recruited to the study. All had similar impairments of the lower limb extensor muscles (Table 1) but were sensate and able to tolerate FES stimulation sufficient to achieve a strong contraction of the relevant muscle groups. No adverse events were recorded during training or testing.

General

In all cases we observed no apparent difference between the maxima for F_{gr} and $\delta F_{gr}/\delta t$ in response to different stimulation protocols at the initial, baseline test sessions. We also noted that, in none of the subjects, was the maximum F_{gr} value apparently different at different test periods between the two stimulation patterns. The intensity of stimulation required during testing, although determined by the individual's tolerance and ability to achieve contraction, was slightly lower in the HF stimulation in the case of Subjects A and D (Table 2), however these differences were relatively small and were not seen in subjects B and C. The mean stimulation intensities during training were effectively identical between SF and HF for each individual.

Subject A (Figures 2a and 3a)

Training: SF→HF.

Both maximum F_{gr} and $\delta F_{gr}/\delta t$ increased in response to the first training, but F_{gr} decreased slightly after the second training period, although $\delta F_{gr}/\delta t$ continued to increase, in particular when HF stimulation was applied.

Subject B (Figures 2b and 3b)

Training: HF→SF.

Following his first training period we observed no apparent change in either maximum F_{gr} or $\delta F_{gr}/\delta t$. Subsequently, following the second training, we noted a substantial improvement in both maximum F_{gr} and $\delta F_{gr}/\delta t$ but the responses did not seem to be determined by the stimulation frequency during the test.

Subject C (Figures 2c and 3c)

Training: HF→SF.

As with Subject B, she demonstrated no apparent change in either maximum F_{gr} or $\delta F_{gr}/\delta t$ between pre-training and the conclusion of

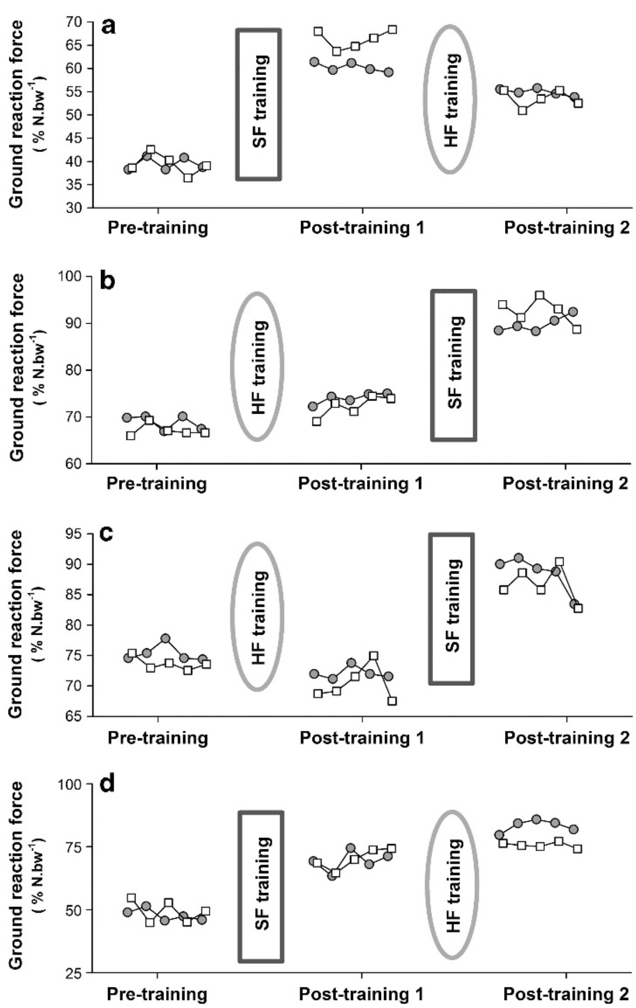

Figure 2 Individual responses of four subjects (**a**–**d**) with respect to maximum vertical ground reaction force. Subjects labelled according to text. Rectangular boxes indicate period of SF training; ovals indicate period of training with HF stimulation. Key: circle = HF maximum F_{gr}; square = SF maximum F_{gr}.

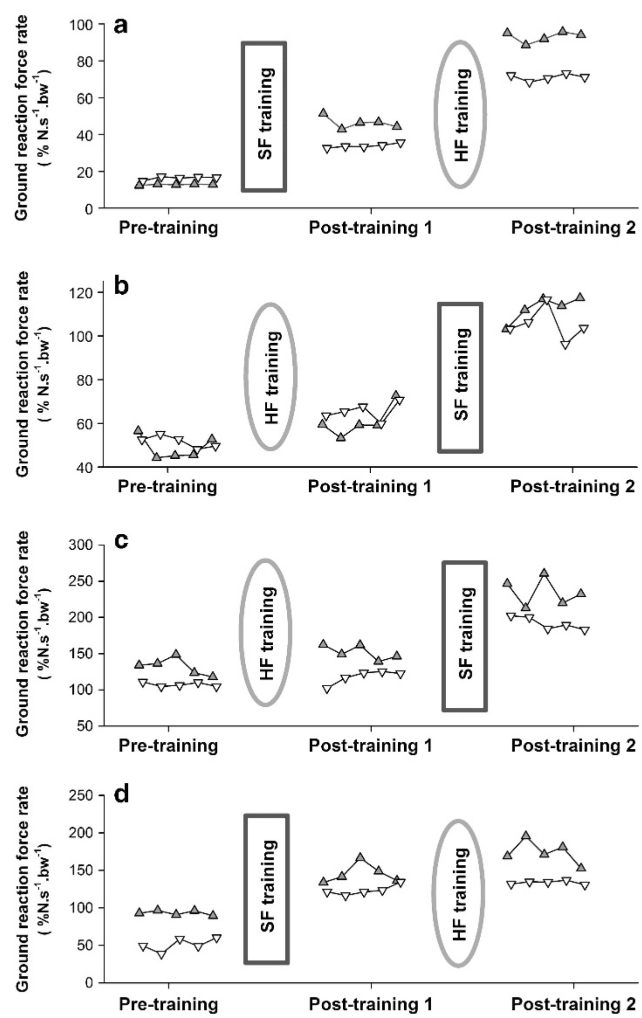

Figure 3 Individual responses of four subjects with respect to rate of ground reaction force generation. Subjects labelled according to text. Training periods indicated according to Figure 2. Key: upward triangle—HF $\delta F_{gr}/\delta t$; downward triangle—SF $\delta F_{gr}/\delta t$.

the first training period. However, after the second training period (with SF stimulation) there was a noticeable increase in both variables.

Subject D (Figures 2d and 3d)

Training: SF→HF.

At initial testing and during subsequent tests, HF stimulation elicited a stronger response in terms of force generation ($\delta F_{gr}/\delta t$), but not with respect to maximum F_{gr}. After the first training period there were apparent increases in both variables, however after the second training period no further increase in ability to sustain weight-bearing was noted, although some further increase in rate of force generation with HF stimulation was observed.

DISCUSSION

This small case series raises a number of interesting findings. We initially sought to compare HF and SF stimulation protocols, both in terms of their immediate effect and with regard to their efficacy in FES-based strength training. There was no obvious difference between the two stimulus frequencies with respect to the absolute force generated by the extensor muscles, assuming that F_{gr} can be considered a valid proxy for this (Figure 2), although there were variable responses from the subjects with regard to current intensity with different frequency modes. However, it did appear that the HF stimulation was somewhat more effective in producing a more rapid force generation ($\delta F_{gr}/\delta t$) than SF, particularly after training.

The use of HF training does not appear to produce any clear gains in maximum force generating capacity. In cases where this was the first training strategy (Subjects B and C), participants showed no change in performance after nine training sessions, but then responded positively to training with SF. When SF was the first training medium, there was a positive response (Subjects A and D) but this did not continue when HF training was applied. With respect to rate of force generation, however, training with either HF or SF stimulation did seem to improve performance, irrespective of the order of stimulation, and gains tended to continue over the two training periods. The specificity of cycling training could potentially limit the transferability of any strength gains to the functional task of standing up, although one might expect that the inclusion of weight resistance training would offset this to some extent. FES-supported cycling is, however, a very common training modality in rehabilitation of people with iSCI, so we feel that our training protocol was contextually valid. There is no clear indication whether the nine training sessions represented an optimal dose; the number of sessions was determined on a pragmatic basis as being within a manageable time frame for participants. Similarly, there was no 'wash-out' period factored into the protocol as this was deemed impractical and largely incalculable in these subjects. Therefore, some carry-over effects might be expected from one training period to the other, although the random cross-over order might reduce this to some extent.

Our preliminary conclusion, based on these results, is that the use of 100 Hz stimulation during cycling and weight resistance training does not appear to achieve functionally significant gains in the maximum force that can be generated by the trained muscles, whereas using the conventional 35 Hz does seem to effect an improvement. On the other hand, 100 Hz stimulation, as a discrete entity, does seem to improve the rate of muscle force generation to a greater extent than 35 Hz, particularly after a period of training.

Study limitations

The relative stability of the observations at each interval for each subject encourages us to believe that the findings of this study are valid for the subjects tested. Clearly there is need for further investigation of these phenomena in light of our findings. We believe, however, that the repetition of a single case, cross-over design has provided a useful insight into the effect of FES-supported training on the performance of standing from sitting in a population notoriously difficult to investigate.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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