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Influence of functional electrical stimulation on gait efficiency in a subject with incomplete spinal cord injury: A case study

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Case Report

Purpose: The aim of the present study was to evaluate the influence of single channel functional electrical stimulation (FES) system on gait efficiency and energy consumption in a subject with incomplete spinal cord injury (SCI). Material and method: The influence of single channel FES system on gait efficiency and energy consumption was investigated in one subject with incomplete SCI. Gait performance of this subject was compared to that of twelve able-bodied control subjects. Three different gait assessment methods were used. They were based on mechanical energy measurement (GEI), oxygen consumption (NE), and heart rate analysis (HRI). Results: As expected, the gait of the able-bodied control subjects was more efficient than that of the subject with incomplete SCI (GEI by 43%, NE by 45%, and HRI by 50%). Use of the FES system, however, increased the gait efficiency of the subject with incomplete SCI (GEI by 40%, NE by 22%, and HRI by 40%). Conclusion: The data suggest that energy consumption can be significantly reduced by using of FES on subjects with incomplete SCI.

Key words: Functional electrical stimulation, Gait, Spinal cord injury.

İnkomplet medulla spinalis yaralanmalı bir olguda fonksiyonel elektrik stimulasyonun yürüyüş yeterliliği üzerine etkisi: Vaka çalışması

Amaç: Bu çalışmanın amacı, inkomplet MSY' lı bir olguda, tek kanallı FES sisteminin yürüyüş yeterliliği ve enerji tüketimi üzerine olan etkilerini araştırmaktır. Gereç ve yöntem: Olgunun yürüme performansı 12 sağlıklı kişi ile karşılaştırıldı. Üç farklı yürüyüş değerlendirme yöntemi kullanıldı. Bu yöntemler, mekanik enerji ölçümü (GEI), oksijen tüketimi (NE) ve kalp hızı analizlerinden temel almaktadır. Sonuçlar: Beklendiği gibi kontrol olgularının yürüyüşünün inkomplet MSY'lı olgudan daha yeterli olduğu gözlendi (GEI %43 oranında, NE %45 oranında, HRI %50 oranında).Bununla birlikte FES sisteminin kullanılmasıyla MSY'lı olguda yürüyüş yeterliliğinin arttığı görüldü (GEI % 40 oranında, NE % 22 oranında, HRI % 40 oranında). Tartışma: Sonuçlar, inkomplet MSY'lı hastalarda FES kullanımının enerji tüketimini anlamlı derecede azalttığını göstermektedir.

Anahtar kelimeler: Fonksiyonel elektrik stimülasyonu, Yürüyüş, Spinal kord yaralanması.

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Functional electrical stimulation (FES) was launched in early 1960's when the first system preventing "foot drop" in persons with hemiplegia was presented.[1] The common peroneal nerve of the affected leg was stimulated during the swing phase of gait cycle whereby ankle dorsiflexion was evoked. Shortly after that, research in the field of FES was started in Ljubljana.[2] As a result of the research, different versions of peroneal nerve stimulators were developed for subjects with hemiplegia and incomplete SCI.[3]

It was found that subjects with incomplete SCI are appropriate candidates for the application of FES to their lower extremities[1]. In these subjects voluntary motor control, proprioception and sensation are usually preserved to some extent. The use of single and multichannel FES in the rehabilitation of subjects with incomplete SCI has been described.[4-6] Stimulation of peroneal nerve in subjects with incomplete SCI causes flexion response (i.e. simultaneous flexion in hip, knee and ankle joint) and thereby accomplishes the swing phase of walking. Stimulation is triggered by a push-button mounted into the handle of the crutch. In selected subjects with incomplete SCI efficient crutch assisted walking with only single channel FES can be achieved.[6]

The aim of the present study was to evaluate the influence of single channel FES system on gait efficiency and energy consumption in a subject with incomplete SCI. For this purpose, a novel gait efficiency assessment method was developed. The method is based on observation of the time courses of potential and kinetic energy of body's center of mass (COM) during walking. The Gait Efficiency Index (GEI) was derived from the correlation between the two energy components. Gait performances of a subject with incomplete SCI and twelve able-bodied subjects were compared. The results of the newly developed method were compared with the results of two established gait evaluation methods: measurement of oxygen consumption and heart rate analysis.

Material and methods

Twelve able-bodied subjects (8 males and 4 females) and one subject with incomplete SCI participated in the study. All subjects gave written informed consent. The able-bodied subjects had an average age of 27.25±4.37 years (mean±SD), average height of 1.79±0.09 m, and average mass of 72.83±13.66 kg. The male subject with incomplete SCI was 48 years old. The level of injury, which took place 4 years ago, was C3-C4. His body mass and height were 86 kg and 1.67 m, respectively. His left lower extremity was almost completely paralysed. Small voluntary contraction was present only in hip muscle groups. In the left knee and ankle no voluntary movement was observed. Left upper extremity was intact except for the fingers. There was no grip preserved in the left hand. Both right extremities were intact. The subject participated in the rehabilitation programme at the Rehabilitation Institute of Ljubljana. The programme included also unilateral FES of knee extensors, ankle plantar flexors, and peroneal nerve.[7] The subject is using the one-channel FES device Microfes (J. Stefan Institute, Slovenia) in every day life. The device is triggered by a push-button mounted into the handle of the right crutch. FES elicits flexion response in the left extremity. The subject usually walks with a crutch, while sometimes he uses a wheelchair for transportation.

Kinesiological measurements were performed by Elite Motion Analysing System (BTS S.r.l., Italy) with 4 infrared cameras. The cameras were positioned behind the subject. A pair of cameras was placed at each side of the subject in a vertical configuration.[8] Seventeen spherical passive reflective markers were placed on the following anatomical landmarks: two markers on the fifth metatarsal heads, two markers on the lateral malleoli, two markers on the lateral femoral condyles, two markers on the posterior superior iliac spines (these markers were supported by small brackets in order to avoid the marker on one side to be seen by the contralateral pair of cameras), one marker on the sacrum bone (this marker was supported by a pin), two markers on the acromion bones (supported by small brackets), two markers on the lateral humerus epicondyles, two markers on the styloideus process and two markers above the ear canals. The sampling frequency was 100Hz, while the acquired data were filtered by the filter incorporated in the Elite system. Body's centre of mass (COM) height and speed were calculated yielding its potential and kinetic energy. Then the time courses of the potential and kinetic energy were calculated. Both energy components have periodic time courses. The time courses of body's COM potential and kinetic energy were first normalised. Then the cross-correlation (r) of the normalised energy functions was calculated. From the cross-correlation the Gait Efficiency Index (*GEI*) was defined as:

$$GEI = \frac{1}{(1-r)\cdot 10^4} \qquad (1)$$

GEI is a measure of similarity between the time courses of potential and kinetic energy of body's COM. If the correlation between both time courses is good, the exchange between energy components is effective and the gait is energy-efficient. For energy-efficient gait, high values of *GEI* are expected (i.e. r is close to 1), while lower values are expected for energy less efficient gait (i.e. r is close to 0).

Expired air was collected in a meteorological balloon for two minutes while sitting and walking. Prior to the air collection the subjects were sitting for 5 minutes. The results of the air analysis represent the physiologic steady-state data during rest and walking, respectively. Expired air volume and percentile content of O_2 and CO_2 were determined. Samples of expired gas were analysed according to the standard procedures using oxygen analyser MK 200 (J. Stefan Institute, Slovenia), carbon dioxide analyser ULTRAMAT 22P (Siemens, Germany) and flow meter S430A (KL Engineering, USA). Prior to each analysis the measurement devices were calibrated. The values obtained were corrected for STPD (Standard Temperature, Pressure and Dry). The metabolic energy expenditure (E) during walking was calculated:

$$E = k\cdot\left(VO_{2w} - VO_{2r}\right) \quad \left[\frac{J}{kg\cdot s}\right] \qquad (2)$$

where k is energy equivalent of oxygen (Weir factor). VO_{2w} and VO_{2r} are oxygen consumption during walking and rest, respectively. The metabolic energy consumption rate (*NE*) was calculated:[9]

$$NE = E_w - E_r \quad \left[\frac{J}{kg\cdot s}\right] \qquad (3)$$

where E_w and E_r are the energy expenditures during walking and rest, respectively.

The heart rate (HR) was recorded by a system for physiological measurements[10] for 2 minutes during rest and for 2 minutes during walking. Again, the physiologic steady-state data were collected. Average HR and Heart Rate Increase (*HRI*) were calculated:[11,12]

$$HRI = HR_w - HR_r \quad \left[\frac{beats}{min}\right] \qquad (4)$$

where HR_w and HR_r denote average heart rate during walking and rest, respectively.

Each walking trial consisted of two parts: the subjects first sat on a chair for 5 minutes and then walked on a 15 m long walkway at constant speed of 0.4 m/s for 7 minutes. The walking speed was controlled by a mechanism consisting of two wheels (0.1 m in diameter, placed 15 m apart), one of which was powered by a small electromotor, and a wire stretched around the wheels. The angular velocity of the wheel was adjusted by electromotor powering voltage. The subjects followed a marker attached to the wire. In the fifth minute of walking five strides were captured by the optical measurement system. The expired air collection and HR monitoring took place during the last two minutes of resting and walking. The able-bodied subjects walked only once, while the subject with incomplete SCI walked first without any orthotic aid and then by using the FES device.

Results

The results of the able-bodied subjects are displayed in table 1. All three methods show increase of energy consumption with the increase of walking speed. We calculated the Pearson's correlation between the results of *GEI* and the two other gait assessment methods. The results of *GEI* are significantly correlated with both *NE* (r=0.557) and *HRI* (r=0.549).

Averaged time courses of body's COM potential and kinetic energy for five strides are represented in figure 1. While in the able-bodied subjects a 180° phase shift between both energy components is obvious, this is not the case in the subject with incomplete SCI. Another difference is the ratio between peak-to-peak values of potential and kinetic energy. The ratio is 1.5 in the able-bodied subjects, and 5 and 3.5 in the subject with incomplete SCI while walking without FES and with FES, respectively.

Table 1. Results of the three gait assessment methods for the able-bodied subjects.

Subj.	Speed (m/s)	GEI	NE (Jkg^{-1}s^{-1})	HRI (beats/min)
1	0.4	14.81	0.82	3.85
	1.4	2.84	1.89	14.76
	1.8	1.90	2.83	25.79
2	0.4	8.33	1.12	2.96
	1.4	3.28	1.96	10.37
	1.8	1.73	4.49	34.64
3	0.4	23.89	1.02	6.09
	1.4	3.59	2.96	12.00
	1.8	2.20	4.25	43.13
4	0.4	8.11	0.56	3.28
	1.4	1.40	1.76	12.19
	1.8	1.02	4.54	27.49
5	0.4	4.78	1.36	6.72
	1.4	5.38	1.38	22.12
	1.8	2.51	3.09	39.55
6	0.4	14.27	0.40	3.37
	1.4	1.83	2.11	12.98
	1.8	1.35	3.39	21.45
7	0.4	6.08	1.00	3.41
	1.4	1.42	2.44	14.82
	1.8	1.41	6.02	30.34
8	0.4	11.54	1.14	2.64
	1.4	3.07	3.24	12.95
	1.8	1.84	5.37	32.90
9	0.4	3.91	0.78	7.00
	1.4	3.54	1.80	21.00
	1.8	2.86	5.21	41.00
10	0.4	1.71	1.15	3.07
	1.4	2.29	2.46	20.26
	1.8	2.09	6.43	38.66
11	0.4	14.53	2.07	8.40
	1.4	3.52	3.14	11.79
	1.8	1.62	4.63	23.96
12	0.4	10.53	0.94	7.29
	1.4	2.60	2.93	21.96
	1.8	1.86	4.60	30.27
X±SD	0.4	10.21±6.12	1.03±0.42	4.84±2.08
	1.4	2.89±1.11	2.34±0.62	15.6±4.43
	1.8	1.87±0.51	4.57±1.09	32.43±7.09

The results of the three gait assessment methods are represented in table 2 and graphically displayed in figure 2. The values in the figure are normalised to the value of the able-bodied subjects. All three methods show major differences between the gait efficiency of the able-bodied subjects and of the subject with incomplete SCI (*GEI* in the able-bodied subjects is 43% lower than in the subject with incomplete SCI, *NE* is 45% lower, and *HRI* is 50% lower). The results illustrate that the gait of the subject with incomplete SCI is significantly energy-less-efficient than the gait of the able-bodied control group. Performance of the gait of the subject with incomplete SCI with the use of FES is considerably improved as compared to the gait without FES (*GEI* with FES is 40% lower than without FES, *NE* is 22% lower, and *HRI* is 40% lower).

Conclusion

A simple quantitative gait assessment method based on energy exchange analysis during walking was developed. The method can be found useful in clinical gait analysis when evaluating different rehabilitation approaches. In the control group of twelve able-bodied subjects, a good correlation between results of the newly developed method (*GEI*) and the two reference methods (*NE* and *HRI*) was demonstrated. This suggests that *GEI* is a reliable gait assessment method.

In the present study different energy efficiencies of the group of able-bodied subjects and the subject with incomplete SCI were observed. The results of all three gait assessment methods show that the gait of the subject with incomplete SCI is less efficient than the gait of the able-bodied subjects. The difference between the gait of the subject with incomplete SCI with and without using FES is obvious. The data suggest that energy consumption can be significantly reduced by stimulation of the peroneal nerve during the swing phase of gait.

Table 2. Comparison of results of three different gait assessment methods.

	GEI	*NE* (J·kg^{-1}·s^{-1})	*HRI* (beats/min)
Able-bodied	10.21±6.12	1.03±0.42	5.19±2.36
Incomplete SCI walking without FES	17.83±2.47	1.89±0.61	10.35±3.48
Incomplete SCI walking with FES	10.63±1.39	1.48±0.32	6.19±3.05

Figure 1. Averaged time courses of COM potential energy (top) and COM kinetic energy (bottom) in able-bodied subjects (dotted), subject with incomplete SCI walking without FES (dashed) and subject with incomplete SCI walking with FES of peroneal nerve (solid).

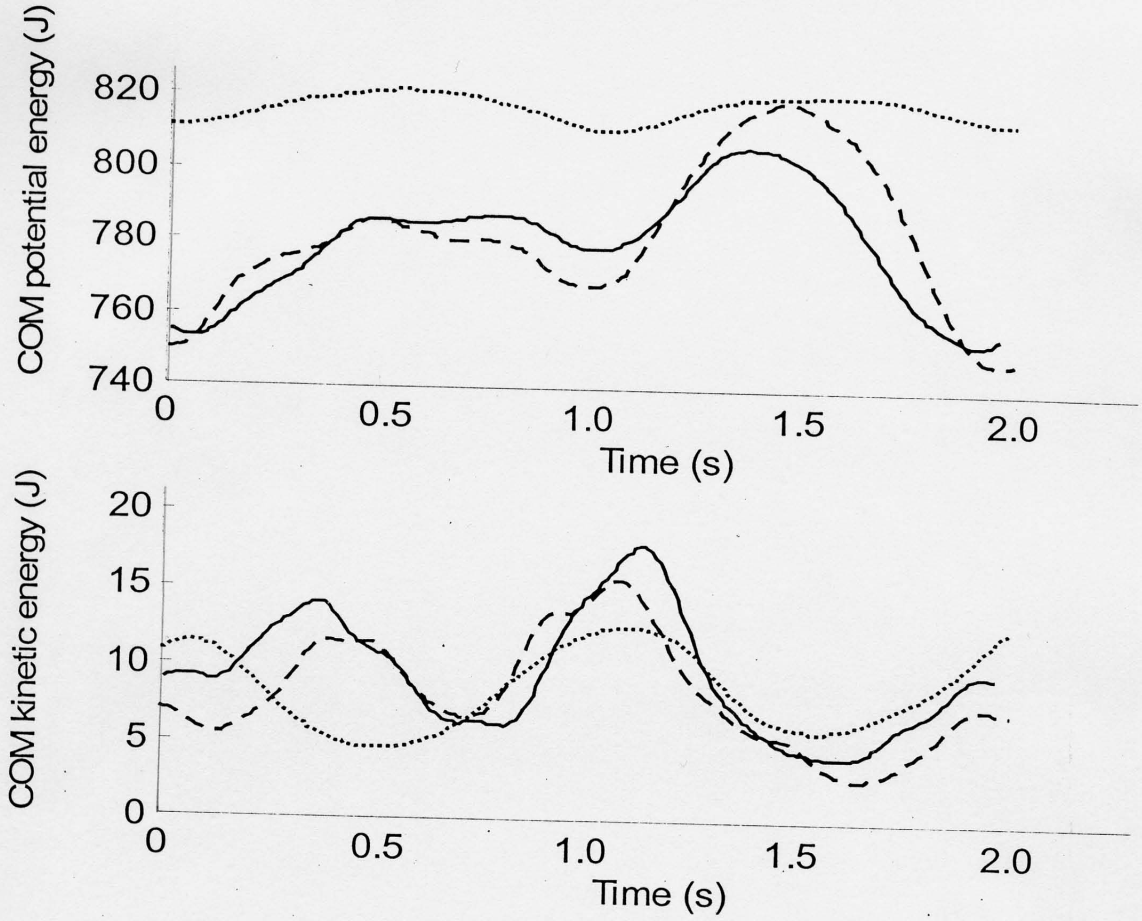
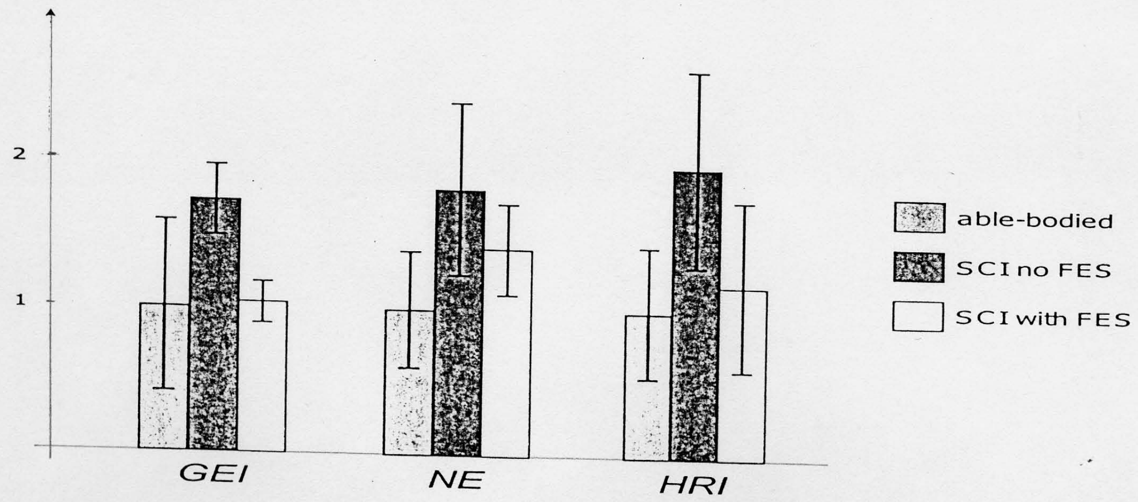


Figure 2. Results of three different gait assessment methods (the values of each method are normalised to the results of normal subjects).



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