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Walking with a powered robotic exoskeleton: Subjective experience, spasticity and pain in spinal cord injured persons

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Abstract.
BACKGROUND: Powered robotic exoskeletons represent an emerging technology for the gait training of Spinal Cord Injured (SCI) persons. The analysis of the psychological and physical impact of such technology on the patient is crucial in terms of clinical appropriateness of such rehabilitation intervention for SCI persons.
OBJECTIVE: To investigate the acceptability of overground robot-assisted walking and its effect on pain and spasticity.
METHODS: Twenty-one SCI persons participated in a walking session assisted by a powered robotic exoskeleton. Pain assessed using a Numeric Rating Scale (NRS) and muscle spasticity, assessed as subjective perception using an NRS scale and as objective assessment using the Modified Ashworth scale and the Penn scale, were evaluated before and after the walking experience. Positive and negative sensations were investigated using a questionnaire. The patient's global impression of change (PGIC) scale was administrated as well.
RESULTS: After the walking session a significant decrease in the muscle spasticity and pain intensity was observed. The SCI persons recruited in this study reported (i) a global change after the walking session, (ii) high scores on the positive and (iii) low scores on the negative sensations, thus indicating a good acceptability of the robot-assisted walking.
CONCLUSIONS: The overground robot-assisted walking is well accepted by SCI persons and has positive effects in terms of spasticity and pain reduction.

Keywords: Spinal cord injury, robotics, rehabilitation, spasticity, pain

1. Introduction

Functional integrity of sensor-motor neural networks at spinal and supraspinal levels is responsible both of normal gait and physiological interactions (Wall, Borg, & Palmcrantz, 2015). Spinal Cord Injury (SCI) is a damage that can disrupt nerve connections,

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altering functional integrity. The incidence rate of SCI in Europe is variable in different reports from 20 to 40 cases per million inhabitants and the prevalence is higher due to a good survival rate after the acute phase of the pathology (Singh, Tetreault, Kalsi-Ryan, Nouri, & Fehlings, 2014).

The spinal lesion can be complete or incomplete. In the former, the spinal cord is completely broken and no motor and/or sensory functions exist below lesion level. In the latter, the spinal cord is partially interrupted and some sensory and/or motor functions exist below lesion level.

The severity of injury is described by the ASIA scale, through using of letters: from "A"- the most severity, to "E"- motor and sensory functions as "normal" (Kirshblum, et al., 2011).

The walking recovery after incomplete lesions is observed in young persons (50 years old or less) in the majority of persons assessed as ASIA D and high percentage of those assessed as ASIA C, (Burns, Golding, Rolle, Graziani, & Ditunno, 1997).

Most of SCI persons are affected by spasticity (66–98%) and at least half of them suffers from severe spasticity (Adams & Hicks, 2005); many SCI persons experience pain sensations (Cardenas, Bryce, Shem, Richards, & Elhefni, 2004) and most of them report low quality of life (Wilson, Hashimoto, Dettori, & Fehlings, 2005). Thus, limited mobility and impaired gait function are major challenges in neuro rehabilitation. Intensive, repetitive task specific training drives beneficial neuroplasticity, enhances functional restitution and improves final outcome (Morawietz et al., 2013; Behrman et al., 2006; Harness et al., 2006; Van Hedel et al., 2010). New devices for body weight support on treadmill and electromechanical orthoses on treadmill are now available for gait rehabilitation in incomplete SCI persons (Alcobendas-Maestro, et al., 2012; Schwartz, et al., 2015). Although the aim of gait rehabilitation cannot be the walking recovery in complete SCI persons, new robotic exoskeletons allow to apply a gait training even in these patients.

Indeed, exoskeletons provide them with a walking experience and a more effective rehabilitation treatment possibly allowing them to ameliorate their performance in daily life (Hussain, 2014).

The robot-assisted gait training can provide more reproducible gait movements compared to conventional gait therapy and reduce the burden on the therapist. It works according to the end-effector principle (foot plates move the feet in a controlled gait pattern) or as exoskeleton robots, where mechanical joints match those anatomical and motors drive movements over these joints to provide an assistance, e.g., leg movements (Shin, Kim, Park, & Kim, 2014). A recent Cochrane review concluded that there is insufficient evidence to conclude that any one locomotor training strategy improves walking function more than another for people with SCI; more research is needed to clarify the effectiveness of gait training, particularly for robotic training (Mehrholz, Kugler, & Pohl, 2012). The robot-assisted gait training in incomplete SCI persons combined with conventional physiotherapy could yield more improvement in ambulatory function than conventional therapy alone (Shin, Kim, Park, & Kim, 2014). Nonetheless, it is not known if the new robotic exoskeleton is well accepted in SCI patients. In particular, severe spasticity and pain have been considered factor of exclusion by the treatment (Sylos-Labini, et al., 2014). Thus, assessing the SCI patients subjective experience of exoskeleton rehabilitation treatments is important with regard to both psychological and physiological aspects. Till now, no findings have been published in this field and no rehabilitation protocol for overground gait training using powered robotic exoskeletons has been proposed as the most effective.

The aim of the present study is to investigate the acceptability of a powered robotic exoskeleton and the subjective and objective assessment of the robot-assisted walking on pain and spasticity in SCI persons unable to walk without electromechanical orthoses.

2. Methods

2.1. Patients

Inclusion criteria: persons affected by complete and incomplete, both traumatic or not traumatic Spinal Cord Injury (SCI); age between 18 and 75 years, body weight less than 100 kg, height between 155 and 190 cm, preserved cognitive function. Exclusion criteria for gait rehabilitation by robotic exoskeleton were: asymmetry in limb length or any important limitation of the Range of Motion (ROM) in hip, knee or ankle, psychiatric disorders.

On these bases, 21 consecutive patients: 4 women and 17 men, mean age 48.1 ± 12.3, range 21–68 years, affected by spinal lesion of traumatic ($n = 14$) and non-traumatic ($n = 7$) origin were enrolled in the study.

Patients were submitted to a neurological visit. Their spinal lesion was classified by ASIA scale (Kirshblum, et al., 2011) to define them as motor

Table 1
Patients characteristics

#ID	Age	Gender	Cause of lesion	Time from acute event (months)	ASIA	Lesion level	WISCI II	SCIM II
P1	46	M	T	37	A	D9	0	72
P2	44	F	T	60	A	D10	0	61
P3	43	M	T	12	A	D3	0	61
P4	57	M	T	54	B	D12	0	72
P5	55	M	T	125	A	D12	0	72
P6	44	M	T	330	A	D6	0	76
P7	60	F	NT (ischemic)	29	D	L1	9	75
P8	21	M	NT (tumor)	38	A	D9	0	71
P9	43	M	T	218	A	L1	0	79
P10	48	M	T	31	D	D12	0	71
P11	25	M	NT (ischemic)	2	D	L2	1	63
P12	46	M	T	294	A	D6	0	67
P13	42	M	NT (tumor)	300	B	C7	0	34
P14	45	M	T	165	A	D3	0	62
P15	56	M	T	153	A	D7	0	68
P16	38	M	T	119	A	D4	0	73
P17	68	M	NT (degenerative)	59	D	L1	0	54
P18	58	M	T	30	A	D4	0	53
P19	40	M	T	225	D	C7	16	79
P20	63	F	NT (degenerative)	69	D	C7	6	52
P21	68	F	NT (tumor)	227	D	C7	19	65

Legend: T, traumatic; NT, non-traumatic.

complete (ASIA A, $n = 12$, ASIA B, $n = 2$) or incomplete (ASIA D, $n = 7$) and assess their lesion level.

The lesions level was low cervical (C7, $n = 4$), dorsal ($n = 13$) and high lumbar (L1-L2, $n = 4$) (Table 1). Most of patients were in a chronic stage: only two were within the first year after the acute event: the time from acute event onset ranged from 2 to 330 months (mean, SD: 116.3 ± 97.2 months).

The degree of autonomy was assessed using the Spinal Cord Independence Measure (SCIM II) (Catz, et al., 2001) and the walking ability by the Walking Index for Spinal Cord Injury (WISCI II) scale (Ditunno & Ditunno, 2001).

SCIM II values ranged from 34 to 79 (median [IQR]: 68.00 [61.00-72.25); 16 out of 21 recruited patients were not able to walk (WISCI-II = 0), only 5 patients were able to walk as exercise or in the community (WISCI-II ranging from 1 to 19).

Patients were informed about the experimental procedure and signed an informed consent.

2.2. Equipment and experimental procedure

The robotic exoskeleton (Ekso GT, Ekso Bionics, Richmond, CA, USA) (Fig. 1) can be adjusted to fit majority of population (body weight <100 kg, height between 1.50 m and 2.0 m). In order to fit each individual anthropometric size, proper settings have to be adjusted by the physical therapist through the measurements of lower extremity and waist in supine posture.

Fig. 1. A spinal cord injured patient during the robot-assisted walking.

On the day of the study the settings of the robotic exoskeleton were adjusted for each patient

by measuring the length of the proximal and the distal segment of the two limbs, the distance between the two limbs (i.e., pelvis width) and the bilateral Range of Motion (ROM) at ankle, knee and hip joints (Strausser et al., 2011).

After this operation the patient sat on a chair where the robotic exoskeleton was previously positioned and additional adjustments on the knees, ankles and feet were completed. When the patient was ready, an automatic procedure for standing up was launched by the operator and the patient was assisted during walking.

The powered robotic exoskeleton is strapped over the users clothing with minimal adjustments. During the training session the physical therapist actuated steps using a push button: the patient progressed from sit to stand posture, to walking using an assistive device (rollator). The stepping was carried out by the actuators embedded into the mechanical structure of the robotic exoskeleton: the control modality was passive and induced locomotion even in complete SCI patients.

The exercise session lasted about 40 minutes; in this total time there were period of walking, alternating to resting period; the total time of walking ranged from 7 to 25 minutes (depending to the subject resistance) and the traveled distance between 30 and 90 meters.

2.3. Outcome measures

Before and after the walking session patients reported their pain and spasticity using a Numeric Rating Scale (NRS) 0–10 points. Spasticity was evaluated through the Modified Ashworth scale (MAS) (Bohannon & Smith, 1987) applied to the three segments of both legs (hip, knee and ankle flexors and extensors) and the spasms were quantified using the Penn Spasm Frequency Scale (PSFS) (Penn, et al., 1989). After the walking task, patients completed a questionnaire prepared ad hoc and reporting the subjective experience (range: 1–7) of "Comfort" (C), "Pain" (P), "Fatigue" (F), "Enjoyment" (E), "Perceived advantages" (A), "Motivation to continue training" (M) and "Suggest to anyone in the same conditions" (S) (Mazzoleni, Turchetti, Palla, Posteraro, & Dario, 2014).

The patient's global impression of change (PGIC) was used to assess as self-report measure the perceived changes in the activity limitations, symptoms, emotions and overall quality of life (Guy, 1976; Wyrwich et al., 2012).

2.4. Statistical analysis

All analyses were performed using the Sigma Stat v3.5 statistical package (Systat Software Inc., San Jose, CA, USA). The perceived pain and spasticity as well as Penn Scale and MAS scores before and after the robot-assisted training session were analysed through separate repeated measures ANOVA. PGIC and the scores of the questionnaire prepared ad hoc for the assessment of the exoskeleton acceptability were analysed through multivariate ANOVAs. Significance was set at $p < 0.05$.

3. Results

The standing time (mean, SD; 34.1 ± 2.7 min) was positively correlated ($R = 0.642$, $p < 0.002$) with the walking time (mean, SD; 14.4 ± 15.6 min) and with the number of steps (mean, SD; 256.7 ± 36.5; $R = 0.751$, $p < 0.0001$), indicating that the walking behaviour was homogeneous among patients.

After the overground walking session assisted by the powered robotic exoskeleton, the perceived spasticity evaluated using a 0–10 points NRS (median [IQR], pre: 2.0 [0.0–4.5]; post: 0.0 [0.0–1.5], $W = -91.0$ $T+ = 0.0$ T- = –91.0, Z-Statistic based on positive ranks = –3.2, $p < 0.001$) (Fig. 2) as well as the assessed spasticity of the three segments of both legs using the MAS (median [IQR], pre: 4.0 [0.0–10.7]; post: 2.0 [0.0–5.2], $W = -91.0$ $T+ = 0.0$ T- = –91.0, Z-Statistic based on positive ranks) = –3.2, $p < 0.001$) (Fig. 3) and PSFS scores (median [IQR], pre: 1.0 [1.0–2.2]; post: 0.0 [0.0–1.0], $W = -66.0$ $T+ = 0.0$ T- = –66.0, Z-Statistic (based on positive ranks) = –3.0, $p < 0.001$) (Fig. 4) were significantly reduced ($F(1,20) = 14.085$, $p < 0.001$).

In contrast, the perceived pain did not differ significantly, but the effect size was quite low ($\eta^2 = 0.137$) (median [IQR], pre: 4.0 [0.0–6.0]; post: 0.0 [0.0–4.0], $W = -49.0$ $T+ = 21.0$ T- = –70.0, Z-Statistic (based on positive ranks) = –1.7, $p = 0.094$). Selecting only the patients who reported pain before the robot-assisted walking session ($n = 12$) a significant pain reduction was observed (median [IQR], pre: 6.0 [4.5–7.0]; post: 2.0 [0.0–4.0], $W = -55.0$ $T+ = 0.0$ T- = –55.0, Z-Statistic based on positive ranks = –2.8, $p = 0.002$) (Fig. 5).

No significant change in the participants without pain before the robot-assisted walking session ($n = 9$) was found (median [IQR], pre: 0.0 [0.0-0.0]; post: 0.0 [0.00–2.5], $W = 6.0$ $T+ = 6.0$ T- = 0.0, Z-Statistic

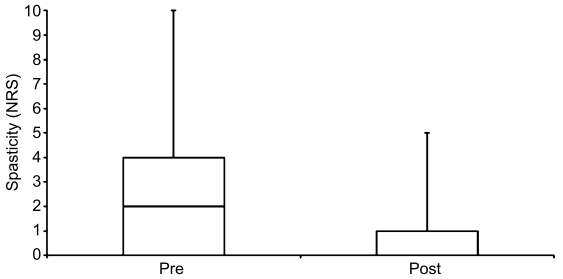

Fig. 2. Subjective assessment of spasticity (NRS 0–10), before (pre) and after (post) the robot-assisted walking (values expressed as median and IQR).

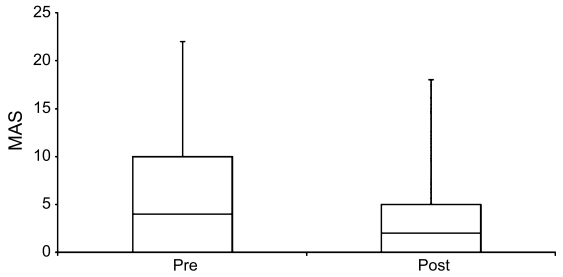

Fig. 3. Objective assessment of spasticity: Modified Ashworth Scale (MAS) scores (sum of three segmental evaluations), before (pre) and after (post) the robot-assisted walking (values expressed as median and IQR).

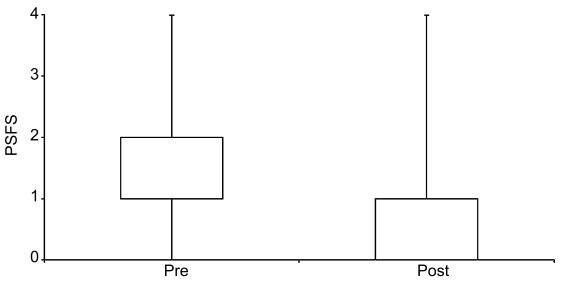

Fig. 4. Penn Spasm Frequency Scale (PSFS) scores, before (pre) and after (post) the robot-assisted walking (values expressed as median and IQR).

(based on positive ranks) = 1.6, $p = 0.250$). The reduction of pain is not correlated to the reduction of spasticity ($R = –0.262$, $p > 0.05$).

The global perception of change expressed by PGIC scores (median [IQR]: 5.00 [2.75–6.00]) and PGIC VAS scores (median [IQR]: 2.50 [2.00–4.00]) indicates that patients experienced a moderate change.

A significant negative correlation was observed between the two subscales of the questionnaire ($R = –0.917$, $p < 0.0001$), which supports the reliability of the patients self report.

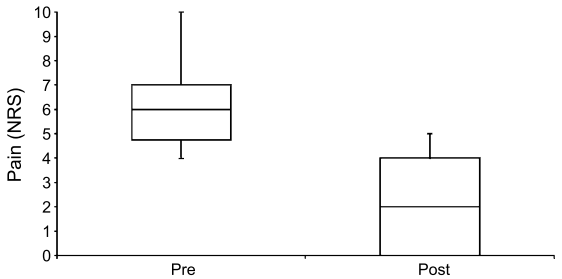

Fig. 5. Subjective assessment of pain (NRS 0–10), before (pre) and after (post) the robot-assisted walking (values expressed as median and IQR).

The questionnaire on the acceptability of the robot-assisted walking indicates high scores of the positive sensations/opinions (median [IQR]: C, 6.0 [6.0–6.0]), E, 6.0 [6.0–7.0], A, 5.0 [5.0–6.0], M, 6.0 [6.0–7.0], S, 6.0 [6.0–7.0], and low scores of the negative experiences (median [IQR]: P, 2.0 [1.0–2.0]), F, 3.0 [2.0–5.0]).

4. Discussion

The results of correlations between standing time, walking time and number of steps highlight how the overground walking assisted by a powered exoskeleton is able to support a gait characterized by a stereotyped behaviour among patients affected by different completeness of lesion, lesion level and walking ability: the robotic device seems to determine the spatio-temporal gait features.

The presented results demonstrate a reduction of muscular spasticity, assessed in terms of patient perception and objective evaluations of tonic spasticity and spasms frequency. The spasticity reduction was observed in previous case reports evaluating the training effects using powered exoskeletons (Esquenazi et al., 2012; Aach et al., 2014). Similar results were found in previous studies where the effects on spasticity during robot-assisted training with BWS on treadmill were investigated (Mirbagheri, et al., 2015; Duffell et al., 2015; Labruyère et al., 2014).

The decrease of spasticity following robot-assisted walking in SCI patients might be explained by the fact that the gait is a physiological and automatic movement and this exercise allows walking in persons who are unable to walk without an assistive device (Mirbagheri, et al., 2015; Duffell et al., 2015). The activation of neuronal circuits involved in walking, though obtained in an artificial way, in SCI persons, is able to reduce the non physiological and under regulated hyperactivation present in spasticity (Mazzoleni

et al., 2015). Replacing lost patterned activation of spinal cord by activating synaptic inputs via assisted movements may help to recover lost spinal inhibition which is the "primum movens" of the spasticity development (D'Amico, Condliffe, Martins, Bennett & Gorassini, 2014). Of course, the effect of a mobilization of muscles usually unused, which leads to muscular fatigue and muscular fuse adaptation cannot be excluded as concurrent cause of the observed spasticity reduction.

A significant pain reduction observed in persons affected by pain can be considered as an additional advantage in favour of the use of robot-assisted walking in SCI persons, as an high incidence of the chronic pain is described in this population (Saulino, 2014).

Previous case reports describe a decrease of pain in SCI persons after robot-assisted walking (Aach et al., 2014; Cruciger et al., 2014; Kressler et al., 2014).

The decreased pain observed after the walking session using the powered robotic exoskeleton could be attributed at least at some extent to the satisfactory psychological status due to the new experience of walking again; the robot-assisted walking may be also considered as a sort of psychological distraction. Endogen endorphins activated by the walking exercise could contribute to the pain reduction as well.

It is well known that sometimes the muscular spasticity is associated with pain and a reduction of spasticity determines a corresponding reduction of pain. In the presented study the absence of correlation between changes of pain and spasticity demonstrates that the muscular spasticity seems not to play a determinant role in the pain decrease.

Based on the presented results the presence of spasticity and pain in SCI persons should be not considered as contraindications to the use of the powered robotic exoskeleton for gait rehabilitation.

The positive robot-patient interaction is supported by the results obtained by the global perception of change and the acceptability questionnaire proposed to the SCI patients recruited in this study.

Based on the effects of the overground robot-assisted walking the adoption of such technology for the rehabilitation of SCI patients is feasible and well accepted.

5. Conclusions

The results obtained in this study provide a significant evidence supporting the acceptability of walking with a powered robotic exoskeleton in SCI patients unable to walk without electromechanical orthoses.

Moreover the results from the subjective and objective assessments of spasticity and pain after the robot-assisted gait training are encouraging enough to suggest its introduction as rehabilitation tool in the Individual Rehabilitation Program of SCI persons.

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Conflict of interest

The authors declare no conflicts of interest.

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