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Energy cost and psychological impact of robotic assisted gait training in people with spinal cord injury: effect of two different types of devices

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Abstract:	Background: In the last years there has been an intense technological development of robotic devices for gait rehabilitation in spinal cord injury (SCI) patients. The aim of the present study was to evaluate energy cost and psychological impact during a rehabilitation programme with two different types of robotic rehabilitation systems (stationary system on treadmill, Lokomat and overground walking system, Ekso GT). Methods: Fifteen SCI patients with different injury levels underwent robot-assisted gait training sessions, divided into 2 phases: in the first phase all subjects completed 3 sessions both Lokomat and Ekso GT. Afterwards, participants were randomly assigned to Lokomat or the Ekso for 17 sessions. A questionnaire, investigating the Subjective Psychological Impact (SPI) during gait training, was administrated. The functional outcome measures were oxygen consumption (VO2), carbon dioxide production (VCO2), Metabolic Equivalent of Task (MET), walking economy, and heart rate (HR). Results: The metabolic responses (7.73 ± 1.02 mL/kg/min) and MET values (3.20 ± 1.01) during robotic overground walking resulted higher than those during robotic treadmill walking (3.91 ± 0.93 mL/kg/min and 1.58 ± 0.44; $p < 0.01$). Both devices showed high scores in emotion and satisfaction. Overground walking resulted in higher scores of fatigue, mental effort and discomfort while walking with Lokomat showed a higher score in muscle relaxation. All patients showed improvements in walking economy due to a decrease of energy cost with increased speed and workload. Conclusions: Overground robotic assisted gait training in rehabilitation programme

	needs higher cognitive and cardiovascular efforts than robot-assisted gait training on treadmill.
Response to Reviewers:	Authors' answers to Reviewers Neurological Sciences We warmly thank Reviewers for helpful comments and criticisms. Note for reviewing purposes - Our comments/answers in bold italic Revisions and corrections in the text all in red bold Reviewer #1: The revision is satisfying. We thank the Reviewer for her/his positive comment. Reviewer #2: Dear authors, the paper addresses a current topic that has been well developed. However, I suggest some changes to be made. We thank the Reviewer for his positive comment. 1. In the introduction section, the part "The present study was undertaken in order to evaluate energy cost and psychological impact in SCI patients undergoing rehabilitation program with two different types of robotic rehabilitation systems: the stationary system with robotic exoskeleton and body weight support on treadmill Lokomat, and the robotic overground walking system, Ekso GT. The outcome measures were oxygen consumption (VO2), carbon dioxide production (VCO2), Metabolic Equivalent of Task (MET), walking economy, metabolic cost of walking, and heart rate (HR Furthermore, SCI patients were invited to complete questionnaire to evaluate the adherence, compliance, motivation and comfort during RAGT. The results might have practical implications for SCI patients in order to optimize the level and type of training rehabilitation with these robotic devices, minimizing the secondary complications such as metabolic aspects of "burnout", fatigue and overtraining syndrome, not yet well evaluated in the literature . " The part that goes from "The results .... in the literature", should be moved before "the present study", and better addressed and argued by linking it clearly to the hypothesis of the study. We agree with Reviewer's comment and the change was made. In the material and methods section, page 5 "In the second phase of training cycle, the participants randomized into 2 groups, performed a training program of 17 sessions (2 sessions / week) using Lokomat (Loko group, 8 subjects) or using Ekso GT (Ekso group, 7 subjects) and not significant differences in subject characteristics, due to subgroup effect, were observed [11]. " Please specify what kind of randomization was conducted. The kind of randomization was specified. Results: In presenting the results, it would have been interesting to know if the patients had any comorbidities. No, all patients had not any comorbities (see in Materials and methods – Participants, p. 4) Conclusions: "As expected, Ekso training resulted more demanding compared to Lokomat training, with a significant increase in metabolic and cardiac responses, suggesting

	cardiorespiratory benefits." this sentence should be better remodeled, because if the patient has heart problems, diabetes or other the choice between the two devices must also be made respecting the real potential of the patient. Furthermore, an interesting aspect to report would have been the motivation for treatment (which can be reported within the study limits) We agree with Reviewer's comment and conclusion section was revised.

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Energy cost and psychological impact of robotic assisted gait training in people with spinal cord injury: effect of two different types of devices

Abstract

Background: In the last years there has been an intense technological development of robotic devices for gait rehabilitation in spinal cord injury (SCI) patients. The aim of the present study was to evaluate energy cost and psychological impact during a rehabilitation programme with two different types of robotic rehabilitation systems (stationary system on treadmill, Lokomat and overground walking system, Ekso GT).

Methods: Fifteen SCI patients with different injury levels underwent robot-assisted gait training sessions, divided into 2 phases: in the first phase all subjects completed 3 sessions both Lokomat and Ekso GT. Afterwards, participants were randomly assigned to Lokomat or the Ekso for 17 sessions. A questionnaire, investigating the Subjective Psychological Impact (SPI) during gait training, was administrated. The functional outcome measures were oxygen consumption (VO_2), carbon dioxide production (VCO_2), Metabolic Equivalent of Task (MET), walking economy, and heart rate (HR).

Results: The metabolic responses (7.73 ± 1.02 mL/kg/min) and MET values (3.20 ± 1.01) during robotic overground walking resulted higher than those during robotic treadmill walking (3.91 ± 0.93 mL/kg/min and 1.58 ± 0.44; $p < 0.01$). Both devices showed high scores in emotion and satisfaction. Overground walking resulted in higher scores of fatigue, mental effort and discomfort while walking with Lokomat showed a higher score in muscle relaxation. All patients showed improvements in walking economy due to a decrease of energy cost with increased speed and workload.

Conclusions: Overground robotic assisted gait training in rehabilitation programme needs higher cognitive and cardiovascular efforts than robot-assisted gait training on treadmill.

Keywords: Spinal cord injury, Robotic rehabilitation, Lokomat, Ekso, Oxygen consumption, Psychological impact

Introduction

Spinal cord injury (SCI) results in a damage of neural signal transmission at and below the level of injury, leading to loss of motor skills and sensitivities. Depending on the severity and level of injury, paralysis of the limb and trunk muscles results in permanent changes in muscle morphology and physiology [1]. Furthermore, the loss of somatic and autonomic control results in a reduction of physical activity and impairment of cardiorespiratory response to exercise. Hence, due to motor planning compromised, patients with SCI are predisposed to secondary complications such as cardiovascular, respiratory, cutaneous, musculoskeletal, and psychological [2]. Therefore, interventions to promote physical activity after SCI are among the top goals of recovery and improvement in quality of life. The abnormal mechanical loading due to repetitive weight-bearing shoulder motions during normal wheelchair-based activities of daily living and mobility, is associated with a high rate of shoulder injury and pain [3], so training with lower limb motility might be more appropriate than exercises with repetitive use of upper limbs. In this regard, robotic devices, and robotic rehabilitation can play a major role in improving physical training in SCI patients.

In the last decades, the important role of robotic gait rehabilitation systems has been recognized in the rehabilitation of various neurological diseases [4, 5]. Several scientific investigations on robotic assisted gait training (RAGT) in SCI patients have showed an improving of neuronal and somatosensory systems, due to body compensation and neural plasticity [6, 7].

Robotic exoskeletons can enable patients with varying levels of spinal injury, to safely and functionally walk for personal mobility or exercise/rehabilitation. Several robotic devices are currently available for gait rehabilitation but the benefits and limitations of each robotic device are not yet well evaluated in the literature. This knowledge would be useful to indicate which is the most effective device to apply in relation to the characteristics of the person, of the spinal lesion and the rehabilitative objective [8]. Furthermore, the enhancement of exoskeleton technologies is essential to improve the devices for real-world use and minimize possible complications such as metabolic aspects of "burnout", fatigue and overtraining syndrome.

In order to obtain further data that can gain knowledge about the use of robotic devices in rehabilitation settings, in this study we evaluate the energy cost and the psychological impact in SCI patients undergoing rehabilitation programme with two different types of robotic rehabilitation systems: the stationary system with robotic exoskeleton and body weight support on treadmill Lokomat, and the robotic overground walking system, Ekso GT. The outcome measures were oxygen consumption (VO_2), carbon dioxide production (VCO_2), Metabolic Equivalent of Task (MET), walking economy, metabolic cost of walking, and heart rate (HR). Furthermore, SCI patients were invited to complete questionnaire to evaluate the adherence, compliance, motivation and comfort during RAGT. The metabolic and psychological dataset obtained might be useful to optimize the level and type of training rehabilitation with these robotic devices and improve physical functions, and consequently quality of life of the SCI patients.

Materials and methods

Participants

Fifteen patients (5 female, 10 male) with motor complete and incomplete SCI were recruited from the Spinal Cord Injury Unit of the University Hospital of Pisa. The accurate characterization of complete and incomplete spinal cord injuries was made by a trained physician according to the American Spinal Cord Injury Association Impairment Scale (AIS) [9].

Before being included in the study, all participants were evaluated to meet inclusion and exclusion criteria checked by the team of researchers.

The inclusion criteria were an age of 16-65 years, height 152-190 cm and weight less than 100 kg, traumatic/non-traumatic SCI, at least 6 months after injury with stable neurological score, complete/incomplete lesion (AIS A, B, C, D at the time of inclusion), patients with Standardized Mini-Mental State Examination > 26 [10].

The exclusion criteria were a diagnosis of neurological impairment other than SCI, presence of transmissible diseases, symptomatic orthostatic hypotension, recent lower-limb fracture or proximal femur bone mineral density (BMD) T-score lower than -3.5, pressure ulcers of the trunk and lower limb, severe reduction in lower limb joint's range of motion (contractures at the hip and knee greater than 20°), untreatable spasticity (Ashworth scale score >3), heterotopic ossification in the joints of the lower limbs, females with pregnancy or who were trying to become pregnant during the study, and any significant comorbid disease that would constitute a risk to participation in physical training as indicated by medical records.

The mean age ± SD was 40 ± 15 years, and the additional subject characteristics are presented in Table 1. All 15 patients enrolled in this study had never used any robotic device before.

The study was approved by the local Ethical Committee of Pisa University Hospital in accordance with the code of Ethics of the World Medical Association (Declaration of Helsinki). Written informed consent was obtained prior to participation in the study and after explanation of the protocol.

Experimental procedure

All subjects underwent a rehabilitation protocol consisting of a familiarization cycle and a training cycle of RAGT divided into 2 phases.

Familiarization cycle was a series of sessions of adaptation, on non-consecutive days and random mode, to practice the two devices. When all patients were accustomed to ambulate safely and continuously with the devices, they were admitted at the consecutive training cycle.

At the beginning of training cycle, phase 1, participants completed 3 sessions, using a body weight support on the treadmill (Lokomat, Hocoma, Switzerland) and after a week of restart, same subjects performed 3 sessions using a powered overground exoskeleton (Ekso GT, Ekso Bionics, USA).

In the second phase of training cycle, the participants randomized into 2 groups trough a computer program (Microsoft Excel Version 16), performed a training program of 17 sessions (2 sessions/week) using Lokomat (Loko group, 8 subjects) or using Ekso GT (Ekso group, 7 subjects) and not significant differences in subject characteristics, due to subgroup effect, were observed [11].

The training sessions (60 min) included transferring into the device, donning and setting, standing, walking, doffing and transferring out of the exoskeleton.

Training protocol

In Loko group, all subjects were supported by a harness-counterweight system, which was set progressively from 50% until to 30% of their body mass, and with guidance force set at 85% to provide a partial assistance throughout the step cycle. The walking speed was kept constant at 1,5 Km/h during the exercise protocol. This setting was selected as the maximal possible velocity without adverse reaction (e.g. spasticity, skin injury, sensory deficits and fasciculation), and the persons were asked to contribute as much as possible to the walking motion.

Ekso group walked in a 10-meter premeasured corridor with close supervision provided by a trained therapist and using a front-wheeled rolling walker. No harness or body weight support system was used. The device was individualized using anthropometric measurements (thigh and shank to adjust length, and hips to adjust frontal plane width), and participants walked with the "ProStep" mode (in which steps are automatically triggered when the device recognizes that the user achieved weight-shifting targets) at safety walking speed [12].

Exercise training intensity was monitored by the rating perceived exertion (RPE) with the Borg Category Ratio (Borg CR-10) [13]. The exertion level was of 4 to 5 on the 10-point Borg CR-10 Scale for all participants in both training, a key factor for comparative exercise protocol at the end of phase 1 of training cycle (T_0) [14]. By using this approach, workload values were monitored, and constantly paralleled in the training progression until the end of treatment.

Data analysis

Metabolic data

Metabolic parameters were evaluated at the end of phase 1 of training cycle (T_0), at the beginning of phase 2 (T_{1beg}), and at the end of 17 sessions of RAGT (T_{1end}).

Respiratory gas exchange (oxygen consumption, VO_2 in mL/min and mL/kg/min; carbon dioxide production, VCO_2 in mL/min; and respiratory exchange ratio, RER in VCO_2/VO_2) was evaluated by a portable metabolic system with a facemask (VO2000, Medical Graphics Corp., USA) (Fig. 1).

Data collected with "Breath by Breath" method were reported as average oxygen consumption every 3-breath ($VO_{2\ avg}$) and assessed as MET. HR (beats per minute, bpm) was recorded with a Polar T31 Heart Rate Monitor, Polar Electro Inc., USA. The HR data were computed as absolute values and expressed in percentage as ratio of HR reserve, calculated by deducting basal HR from the theoretical maximal HR (HR_{max}), following the Tanaka's criteria [15].

When the rate of increasing of VO_2 was < 1mL/kg/min a steady state condition was determine and the cardiorespiratory response was calculated in 3 conditions: during seated rest for 6 minutes (Sitting), during standing with robotic-device for 6 minutes (Standing), and during robotic assisted walking for 10 minutes (Walking). The distance covered during walking was used to calculate walking speed and recorded as meters per second.

Walking economy, the metabolic energy that human walking requires, was calculated as VO_2 consumption related to walking speed (VO_2 mL/m). The power of walking was calculated using standard equations, where $W= 16.58\ VO_2 + 4.51\ VCO_2$, and normalized to body mass (W/kg) [16].

Participant questionnaire

Positive and negative sensations were investigated using a questionnaire. The questionnaire of exoskeleton acceptability was submitted at T_0 to compare the devices and to value the motivation to continue the training.

The questionnaire reportes the subjective experience (range: 1-10) of “Fatigue” (F), “muscle Relaxation” (R), “mental Effort” (Ef), “Discomfort” (D), “Satisfaction” (S), and “Emotion” (E) [17].

Statistical analysis

Data are reported as mean ± standard deviation (SD). The analysis of variance (ANOVA) test was used to evaluate differences among multiple conditions. If positive, the Tukey test was used to test for their statistical significance.

Student's t test was used to evaluate differences between two conditions. Values of $p < 0.05$ were considered to be statistically significant.

Results

All patients tolerated the training protocol well and without reporting immediate or delayed adverse effects such as pain, sensory deficit, muscle contracture or pressure ulcers. No cases of fall or fracture were observed.

Cardiorespiratory and metabolic data

Basal metabolism (measured as VO_{2avg} consumption at seated rest, Sitting) resulted in 2.58 ± 0.67 mL/kg/min for all patients at T_0. This value was not significantly different with standing position Lokomat (Standing Loko) 2.67 ± 0.57 mL/kg/min, but was highly significant with standing position Ekso (Standing Ekso) 3.02 ± 0.48 mL/kg/min ($p < 0.001$).

The $VO_{2\ avg}$ consumption during walking was significantly higher with Ekso than Lokomat: 7.73 ± 1.02 mL/kg/min and 3.91 ± 0.93 mL/kg/min ($p < 0.001$) (Fig. 2).

No significant differences were observed at T_0 between sitting and standing in Lokomat regardless HR data, while a significant increase was found between sitting and standing in Ekso (76 ± 12 bpm and 85 ± 9 bpm, respectively, $p < 0.001$). During walking, the HR response with Ekso was significantly higher with Ekso than Lokomat (100 ± 13 bpm vs 84 ± 9 bpm, respectively, $p < 0.001$) (Fig. 2).

Higher MET values were observed during Ekso training (3.20 ± 1.01) than during Lokomat training (1.58 ± 0.44) ($p < 0.001$).

As far as walking economy is concerned, Ekso group showed a significantly higher values than Loko group: 1.41 ± 0.34 mL/m vs 0.16 ± 0.04 mL/m ($p < 0.001$), and the power of walking was 2.88 ± 0.57 W/Kg and 1.18 ± 0.42 W/Kg ($p < 0.001$), for Ekso and Lokomat, respectively.

We found that no difference in the results of the subgroup effect at T_{1beg} [11]: the walking VO_{2avg} resulted in 8.50 ± 0.62 mL/kg/min and 3.97 ± 1.03 mL/kg/min for Ekso and Loko groups, respectively. The same happened for HR response.

At the end of the total 17 session training (T_{1end}), the walking VO_{2avg} showed a significant decrease in the Ekso group (5.64 ± 1.64 mL/kg/min, $p < 0.001$); no difference was observed in the Loko group (Fig. 3). HR data showed a decrease in both groups, but not significant. Ekso training lowered significantly the calculated percentage of heart rate reserve (%HRR) from 23.4 ± 9 to 14.5 ± 3.2, $p < 0.05$. In the Loko group there was a trend toward decreasing, but not significant.

MET decreased significantly only in Ekso group (from 3.33 ± 1.03 to 2.23 ± 1.05, $p < 0.01$), but overground walking speed increased from 0.09 ± 0.02 to 0.145 ± 0.02 in Ekso group, therefore in Loko group, body weight support system was set from 50% to 30% of body mass to keep similar RPE.

Data obtained on evaluation of walking economy are presented in Fig. 3. Loko group did not show statistically differences between T_{1beg} and T_{1end} phases, whereas a significant decrease was observed in Ekso group (from 1.44 ± 0.38 mL/m to 0.53 ± 0.06 mL/m, $p < 0.001$).

As far as the power of walking is concerned, we found that power between T_{1beg} and T_{1end} phases decreased significantly in Ekso group (from 2.87 ± 0.56 W/kg to 1.89 ± 0.40 W/kg, $p < 0.001$). No significant differences were observed in Loko group (Fig. 3).

No significant differences were reported in RER data for each time and walking scenario.

Participant questionnaire

We found a similar positive effect with high scores in Satisfaction (S) and Emotion (E) in both RAGT: 7.2 ± 1.9 S and 4.4 ± 3.4 E; 6.6± 2.2 S and 5 ± 3.3 E for Loko and Ekso groups, respectively. Low scores of Fatigue (F), mental Effort (Ef), and Fear or Discomfort (D) were observed in Loko group, whereas overground walking resulted in higher and significant scores of all these 3 items: 2.8 ± 1.9 F, 3.2 ± 1.6 Ef, 0.8 ± 0.2 D and 5.5 ± 1.6 F, 6.5 ± 1.9 Ef, 3.4± 1.3 D, respectively ($p < 0.05$). Lokomat training was perceived to be less demanding when compared to the Ekso training and a higher score in muscle Relaxation (R) was found: 5.4 ± 2.9 vs 4.6 ± 2.1, respectively (Fig. 4).

Discussion

In the present study, we investigated energy cost and psychological impact in SCI patients undergoing rehabilitation programme with two different types of robotic rehabilitation systems: Lokomat and Esko are currently used in a clinic rehabilitation training protocol, but the comparison between two types of RAGT has not been yet studied in detail.

Metabolic cost of sitting and standing with Lokomat and Ekso

VO_{2avg} consumption at seated rest was significantly lower than in the general population [18], in agreement with data reported by Collins et al. [19]. Consequently, MET was 29% lower compared with age-matched able-bodied subjects [20]. We determined that 1MET was equivalent to 2.58 mL/kg/min, since using the standard value of 3.5 mL/kg/min, the level of work, stress and strain in SCI patients might be underestimated. Probably, our results may be related to body composition changes, mainly due to the loss of metabolically active muscle mass and to the infiltration of fat in intramuscular and visceral sites [21].

Changing body posture from sitting to standing caused a greatest and significant cardiorespiratory demand only for Ekso device. The differences in metabolic costs of RAGT devices might be explained by different biomechanical parameters during the two conditions. In Lokomat set up there are specific constraints in the sagittal plane for hips, legs and ankles, moreover chest and trunk are limited in the free movements by weight support harness. The less constraints for chest and trunk in Ekso set up leads to an increment of metabolic demand, probably due to higher muscle activation during standing position even more evident during walking training [4].

Furthermore, the metabolic cost between sitting and standing with Ekso might increase a non-exercise activity thermogenesis (NEAT), which is not related with exercise or daily living activity, but involves an enhance in energy expenditure [22]. The available of Ekso, or other similar/personal device, in daily living could be an optimal strategy to replace sitting with standing position and increase the daily energy expenditure. On the basis of our data, the replacement of 6 hours/day of sitting with a NEAT activity, a 65 kg SCI person would expend an additional 50 kcal/day, predicting a loss of 2.0 kg of body fat mass in 1 year [23].

Metabolic cost of walking with Lokomat and Ekso

In our study, to compare the two RAGT protocol, particular attention has been devoted to examine exercise level using RPE.

Although RPE scores were similar in both RAGT training (4-5/10), Ekso group subjects had a higher VO_2 consumption than Loko group subjects.

In fact, at the T_0, our results show that walking with Lokomat increase the metabolic cost of 46% from standing, with a corresponding walking economy of 0.16 ± 0.04 mL/min and a power of 1.18 ± 0.42 W/Kg, whereas walking with Ekso increase the energy cost of 156% from standing, with a walking economy of 1.41 ± 0.34 mL/min and a power of 2.88 ± 0.57 W/Kg.

Furthermore, at this time MET value for Loko group, equal to 1.58 ± 044, correspond to a low physical activity level, while in Ekso group the MET value of 3.20 ± 1.01 achieve a moderate intensity level according to the American College of Sports Medicine's (ACSM) criteria [24].

These results are probably due to different postural stability during standing and balance in Lokomat and Ekso walking, depending critically on motor function in the trunk muscles, which could vary with the control skills in SCI patients [25]. A recent study has reported a higher muscle trunk activity by electromyography analysis (EMG) during the Ekso walking conditions than Lokomat, and EMG activation patterns during Ekso walking were comparable to EMG patterns during regular treadmill walking in able-bodied individuals at similar speeds [26]. Walking with Ekso elicited a significantly higher lateral pelvis displacement (“ProStep” mode) compared to walking with a fixated pelvis as in Lokomat device. In addition, upper-extremity muscle activity and laterally weight shifting might have contributed to the differences observed between training devices.

Lokomat requires less active participation, since legs are moved by the device and the trunk is supported by a harness and this resulted in less trunk acceleration in all direction in line with previous findings in the literature [27].

So the greatest VO_2 increase, between standing and overground walking with Ekso, could be explained by the active contribution of the upper limbs and trunk necessary for weight shifting and balance during walking.

Metabolic cost of training sessions with Lokomat and Ekso

The main objective of this study was to compare physiological responses during a training period of twenty session using Lokomat or Ekso in SCI persons.

At T_{1end}, as expected, our data show an increased workload, with adaptation to training, with an increase in speed in the last sessions of overground walking in Ekso group, and a reduction of body-weight support (BWS) and guidance force in Loko group.

Despite the RPE was similar, surprisingly we found a concomitant reduction of the metabolic cost in both groups.

Our data show that the Loko training did not reach sufficient cardiorespiratory demand, attesting to low intensity levels (1.0 to 2.9 METs), in line with a previous research which reported metabolic costs of Lokomat versus manual assisted walking on treadmill [28]; although an increase of energy expenditure was evidenced when subjects were asked to maximize their effort during robotic-assisted walking [29]. Probably, despite the decrease of BWS and guidance force during protocol training, participants might have limited the ability to exert a maximal effort. Furthermore, in Lokomat setting, the stabilization of the trunk and the pelvis may reduce voluntary muscle activity and energy expenditure. In Ekso group, at the beginning participants reached a moderate level of cardiorespiratory fitness, which decreased at lowest level at the end of training.

At T_{1beg}, our results were in agreement with previous studies that measured cardiovascular capacities using overground walking exoskeleton at similar training session [30], but at T_{1end}, our data resulted lower than other reports [31], even if energy cost was sufficient to induce moderate exercise level during all training. It is important to note that the increase of speed and workload combined with the decrease of energy cost resulted in improved walking economy for all participants. Moreover, in Ekso group, improvements in overground walking speed might be due to increased proficiency and skill acquisition.

Lokomat treadmill walking, though different levels of guidance force and BWS, attend smaller movement amplitudes of thorax and pelvis than Ekso ones, and only the sagittal tilting of the pelvis was higher during robot-assisted treadmill walking than during overground walking. This evidence explains the different decrease in metabolic cost for the two RAGT devices, which we found significantly only for powered overground exoskeleton.

Although patients were encouraged to contribute to motion in both RAGT walking conditions, differences in energy costs and consequently cardiorespiratory benefits were evident, suggesting a greater positive effect with Ekso training. Nevertheless, a study shows that also a low-intensity training, similar to our Lokomat training level, can improve physical capacity in untrained subjects [32].

HR and RPE data

Comparing RAGT devices during standing and walking at T_0, the higher HR values for Ekso group may be due to the increased effort of the trunk and upper limbs to maintain standing balance, and use of trunk and shoulder muscles required for weight shifting and balancing during walking. Whereas, Lokomat did not report significant increase in HR during standing and walking. The subsequent %HRR values were higher in the participants using Ekso than those using Lokomat indicating greater effort for walking while using the powered exoskeleton.

However, for both RAGT, %HRR was found lower at the last training session than the first session, but only in Ekso group, decreased significantly, suggesting an improved cardiovascular efficiency.

Ginis et al. [33] recommend that people with SCI should carry out an aerobic exercise performed at a moderate to vigorous intensity (about 30-60%HRR) at least twice a week, but in our study this level was never reached except partially at the beginning and only for Ekso group. Interestingly, we did not find significantly RPE differences between RAGT training groups. Indeed, RPE was in the range from 4 to 5 for Ekso and 3 to 5 for Lokomat ("fairly light" to "somewhat hard") that was supported by the relative low increase in HR measure, in line with other literature data [34, 35]. Moreover, HR trend was constant in all patients without an abnormal increase (at different workloads) during the entire protocol. This finding highlights a good venous blood return volume and a good sympathetic vasomotor regulation in our patients, so the ambulatory use of standing and walking with RAGT at low level might not exacerbate or prevents a possible cardiovascular drift effects. This is related by Frank-Starlings mechanism by increased venous return and end-diastolic ventricular volume that could arise from a peripheral vasoconstrictor response [36], which were documented during electrically induced leg ergometer training and arm-crank exercise in SCI individuals [37].

Participant questionnaire - RAGT acceptability

The analysis of the psychological and physical impact of RAGT experience on the SCI patients is crucial in terms of clinical appropriateness of such rehabilitation

Assessing the subjective experience of exoskeleton rehabilitation treatments in persons with SCI, is important with regard to both psychological aspects and the adherences at long term of rehabilitation. As expected, Emotion and Satisfaction had the highest scores both in groups, considering that RAGT enable SCI persons to stand upright and walk in independence way. Significant difference scores resulted in Fatigue, Discomfort and Mental effort item. The high values in Ekso group suggest that exoskeleton requires more involvement in body and mental demand, indeed these subjects reported greater attention to the push-off during the swing and for the stabilization of the system. Since a local muscle fatigue is supported by RAGT action, which decrease the physical demand, these data might be suggest an important role of "central" fatigue factor [38].

Conclusions

As expected, Ekso training resulted more demanding compared to Lokomat training, with a significant increase in metabolic and cardiac responses, suggesting cardiorespiratory benefits. However, the presence of cardiovascular disorders, respiratory disorders or metabolic diseases should be carefully investigated before choosing the robotic divice. Nevertheless, our results indicate a positive training effect with both RAGT devices, associated with faster walking speed in Ekso group and higher workload in Loko group. This may provide evidence to support of their routine use for persons with SCI. However, we should mention that this is a preliminary open study with the limitation of small sample size study population and further studies with a larger sample size and an evaluation of the existence of a remote carry-over effect (follow-up) are needed. In addition, other parameters could be evaluated providing wearable devices to SCI patients (e.g. sport bracelets that automatically identify the user's active and analyze various activity types to produce detailed training records). Furthermore, our study shows that the robotic approach is well accepted and tolerated by the patients, so that overground exoskeleton system can be envisioned as a device that persons with SCI could use in their daily lives to improve physical conditioning and fitness. In this regard, our study might represent a spur for future study designs to better understand the needs and motivational dynamics of patients to adhere to a rehabilitation programme with robotic devices.

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Disclosure of interest

The authors declare that they have no competing interest. The authors also declare that results of this study are presented clearly, honestly and without fabrication, falsification or inappropriate data manipulation.

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Figure captions

Fig. 1 Overview of a partecipant walking with the RAGT devices used in experimental protocol:

A) body weight support on the treadmill (Lokomat, Hocoma, Switzerland)

B) powered overground exoskeleton (Ekso GT, Ekso Bionics, USA)

During metabolic assessments a portable metabolic system with a facemask (VO2000, Medical Graphics Corp., USA) is used

Fig. 2 The box-plots of oxygen uptake (VO_2) and heart rate (HR) at each condition (Sitting, Standing and Walking) for Lokomat (Loko-grey) and exoskeleton Ekso (Ekso-black) groups. Solid line indicates significance between RAGT devices, and dashed line indicates significance between conditions in same group: $p < 0.05$*, $p < 0.001$***

Fig. 3 The box-plots of performance parameters during both training protocols: VO_2 consumption (mL/Kg/min), Walking economy (mL/m), Metabolic cost (W/kg) for Lokomat (Loko-grey) and exoskeleton Ekso (Ekso-lack) groups. Significance within RAGT protocols, $p < 0.001$***

Fig. 4 Subjective Psychological Impact score in the two different training groups. Triangles and circles indicate the values for Lokomat (Loko-grey line) and exoskeleton Ekso (Ekso-black line) groups measured at the end of phase 1 of training cycle (T_0), respectively

Fig. 1

A B

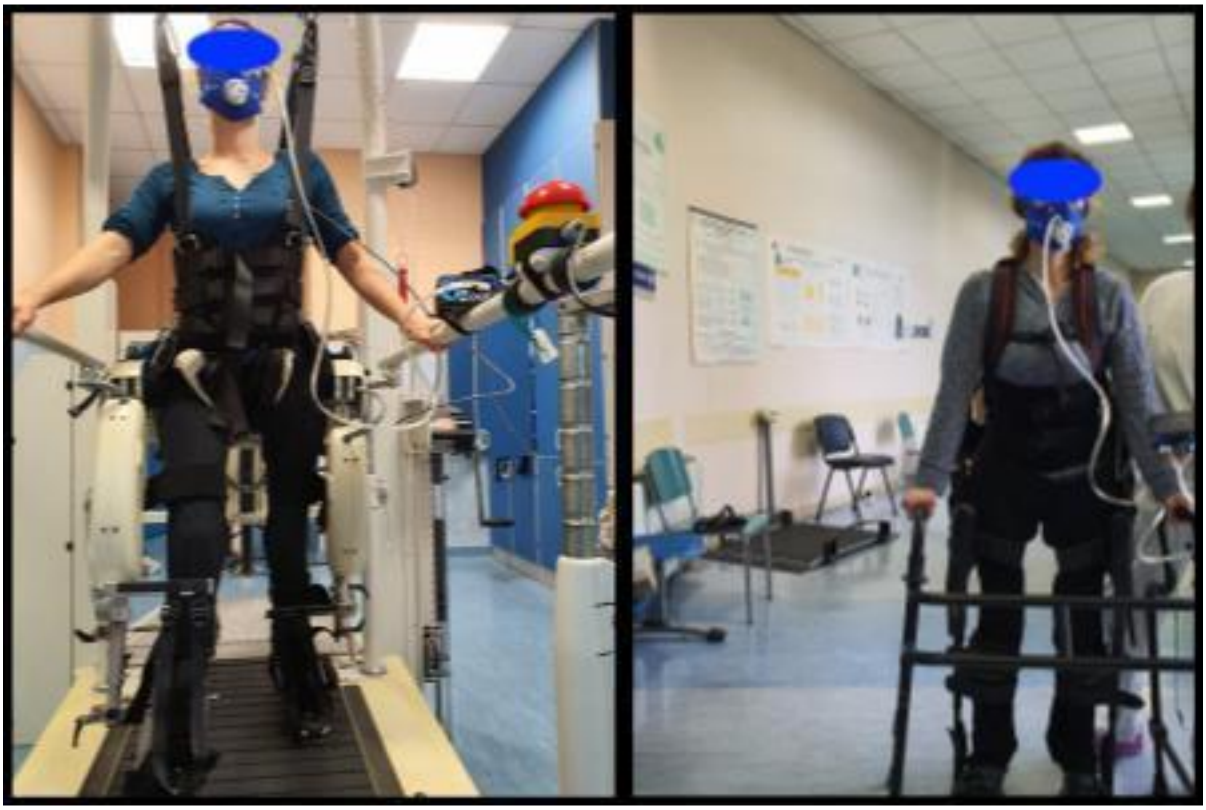

Fig. 2

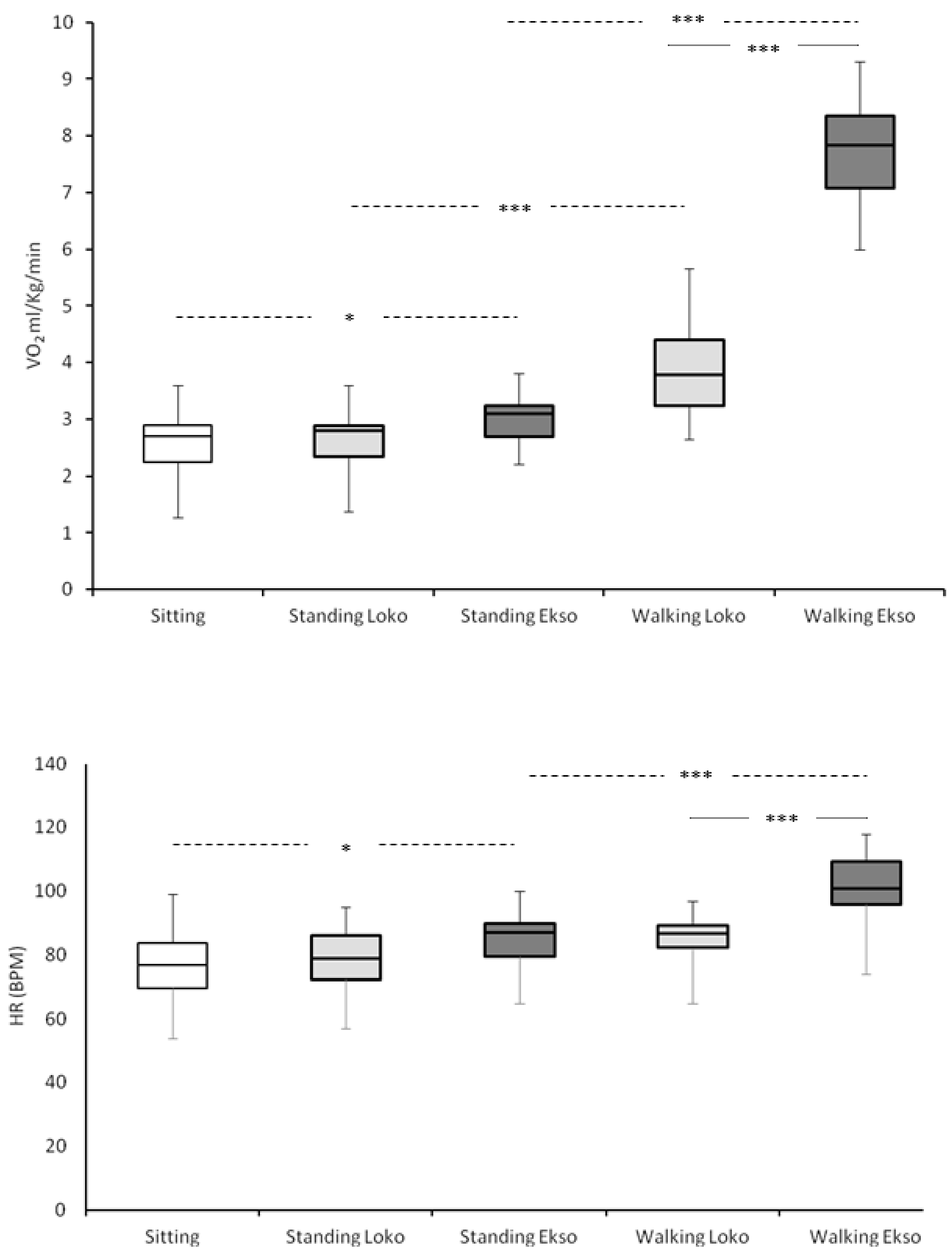
10
9
8
7
6
5
4
3
2
1
0
VO2 ml/Kg/min
***
***
***
*
Sitting
Standing Loko
Standing Ekso
Walking Loko
Walking Ekso
140
120
100
80
60
40
20
0
HR (BPM)
***
***
*
Sitting
Standing Loko
Standing Ekso
Walking Loko
Walking Ekso

Fig. 3

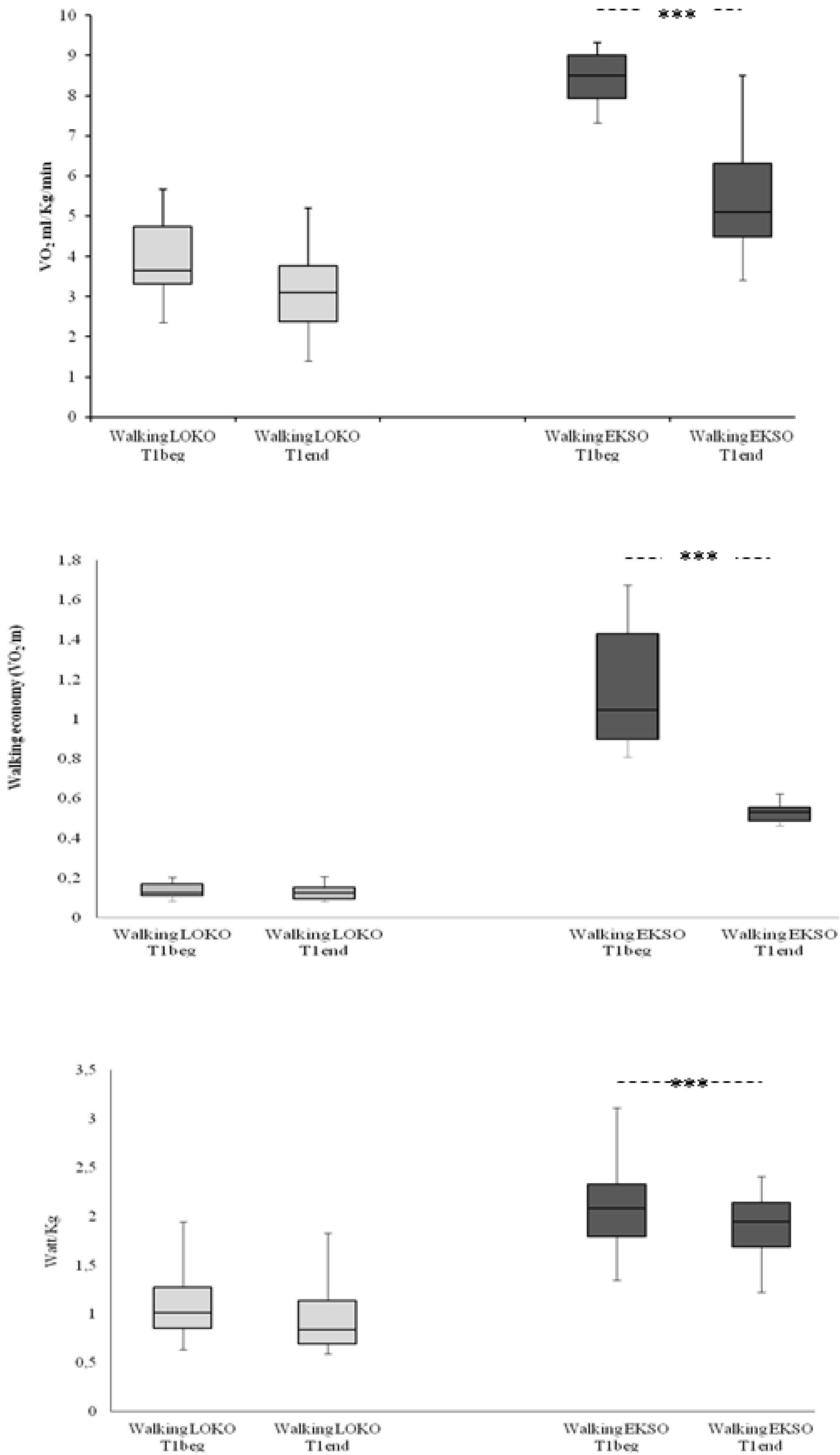
VO2 ml/Kg/min
Walking economy (VO2/m)
Watt/Kg
***
WalkingLOKO T1beg
WalkingLOKO T1end
WalkingEKSO T1beg
WalkingEKSO T1end

Fig. 4

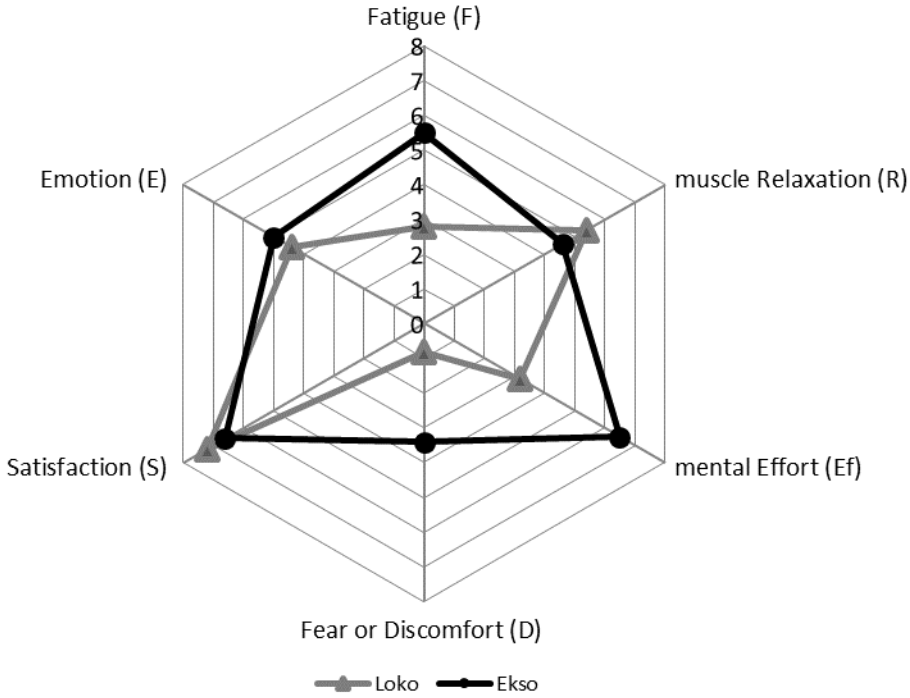
Fatigue (F)
muscle Relaxation (R)
mental Effort (Ef)
Fear or Discomfort (D)
Satisfaction (S)
Emotion (E)
0
1
2
3
4
5
6
7
8
Loko
Ekso

Table 1 Demographic characteristics of the study partecipants

Subject group	Sex	Age (years)	ASIA	LOI	BMI (Kg/m^2)	Time post-injury (years)
Loko 1	M	29	A	T12	16,7	3
Loko 2	M	52	A	L3	24,0	3
Loko 3	M	16	B	C6	16,9	2
Loko 4	M	49	C	L1	22,7	1
Loko 5	M	65	D	T12	26,4	4
Loko 6	F	57	D	L1	24,6	1
Loko 7	F	31	C	T12	27,1	1
Loko 8	F	62	C	T12	23,1	1
Ekso 1	M	26	A	L1	17,9	3
Ekso 2	F	27	B	L2	21,9	3
Ekso 3	M	40	B	L1	23,5	3
Ekso 4	F	26	A	L1	16,9	2
Ekso 5	M	24	B	C4	24,9	2
Ekso 6	M	43	B	L1	18,6	5
Ekso 7	M	52	C	C5	26,8	3

Abbreviations: ASIA, American Spinal Injury Association; BMI, body mass index; LOI, level of injury